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A discrete Forest in a continuous Landscape

Investigating Interactions between Natural Resource Management and Sustainable Development

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The way things look is not always the way things are.

Nassauer, J.I. (1992) Landscape Ecology, Vol. 6, p. 239.

Table of Contents

List of Figures

List of Tables

Summary

Forests are key ecosystems of the earth and attributed with a large range of functions. Many of these functions are beneficial to humans and referred to as ecosystem services. A sustainable development requires that all relevant ecosystem services are quantified, managed and monitored equally. The services attributed to ecosystems are thus the target for natural resource management.

The main hypothesis of the thesis is that the spatial and temporal domains of relevant services do not comply with a discrete forest ecosystem. As a consequence, the services are not quantified, managed and monitored in an equal and sustainable manner. The thesis aims were therefore to test the hypothesis, establish an improved conceptual approach and provide the spatial applications for relevant land cover and structure variables.

The study was carried out in western Switzerland primarily based on data from a countrywide landscape inventory. The landscape inventory is part of the third Swiss national forest inventory and assesses continuous landscape variables based on a regular sampling of true color aerial imagery. Land cover variables were additionally derived from passive sensor data of Landsat 5 TM and land structure variables from active sensor data of a small footprint laserscanning system.

Results confirmed our hypothesis as relevant services did not scale well with the forest ecosystem. Instead, a new conceptual approach is described for natural resource management aiming at sustainable development that quantifies the services as a continuous function of the landscape and not only of a discrete forest ecosystem. The explanatory landscape variables are thus called continuous fields. And the forest becomes a dependent and function driven management unit. Continuous field mapping methods were established for land cover and structure variables.

In conclusion, the discrete forest ecosystem is an adequate planning and management unit. But monitoring the sustainable state and trend of services requires that they are quantified as a continuous function of the landscape. A sustainable natural resource management iteratively combines the ecosystem with the gradient approach.

Résumé

Chapter 1

Introduction

1.1 Forest Ecosystem

Forests are key ecosystems of the earth covering almost 4 billion ha, i.e. about 30% of total land area (FAO 2006). At former times, forest cover was even as high as 6 billion ha, i.e. about 44% of the land (Sharma 1992, Woodwell 2001). Forest cover spans large biogeographic gradients ranging from polar, boreal, temperate, subtropic to tropic forests, of which 36.4% are still considered primary forest with native species composition, and natural or near-natural cycling (FAO 2006). From an administrative point of view, forest distribution is uneven. The five most forest-rich countries (the Russian Federation, Brazil, Canada, the United States and China) account for 53%, and the ten most forest-rich countries include 66% of global forest area.

Trees are the dominating landscape element determining forests. Global tree diversity is roughly estimated to be as high as 100,000 species (Oldfield, Lusty & MacKinven 1998) exhibiting a great variety of physiological and morphological adaptations to environmental conditions (Huston 1994, Larcher 2003). The upper elevational limit of tree distribution lies above 4'000 m a.s.l. at the equator, but decreases with increasing latitude to below 1'000 m (Körner 1998). Spatial arrangement and composition of tree species structure the earth's surface and create diverse climatic environments. As a result, two thirds of the earth's terrestrial species are found in forests (Salim & Ullsten 1999). For birds and amphibians forests are even the major habitat (Baillie et al. 2004). Forests do not only form complex ecosystems with respect to biotic, but also abiotic gradients. Water, carbon, nitrogen and mineral cycles, as well as energy flows, play a considerable role at the global scale (Waring & Running 1998, Kimmins 2004). Global growing stock of forests is estimated at 434 billion m^3, i.e. an average of 110 m^3/ha, storing 283 Gt of carbon in the above ground biomass or 638 Gt within the entire ecosystem (FAO 2006).

1.2 Forest Services

Forests are the green mantle (Salim & Ullsten 1999) that structure the earth's surface, drive essential cycles and energy flows, and are home to a considerable number of life forms. Forests thus represent a large range of local to global functions, of which many are critical to humans. Ecosystem functions that humans benefit from directly or indirectly are called ecosystem services (Daily 1997, Costanza et al. 1997). Ecosystem services have been subdivided into goods, i.e the physical ecosystem products, and services, i.e. the physiological ecosystem processes. However, availability of a physical product ultimately depends on the underlying physiological processes. As a consequence, today's nomenclature uses mostly the general term of ecosystem services (Millennium Ecosystem Assesment 2005).

Humans critically depend on forest services since early history, with varying services dominating during different eras: food, shelter, timber, fibre, fire wood, tools, and war equipment (Winters 1974). Lately, humans have realised that forest services and their dependency extend beyond the goods, but include the ecological processes as well. So today's forest services considered range from *provisioning* (e.g. timber, fibre, fuel, food and genetic resources), to *regulating* (e.g. air/water purification, climate regulation, pest and natural hazard control), *cultural* (e.g. aesthetics, educational, recreational, spiritual and religious values) and *supporting services* (e.g. nutrient cycling, carbon sequestration, soil formation, primary production) (Millennium Ecosystem Assessment 2005). Globally, the primary service of 34% of the present forest area is production, 11% conservation, 9% protection, 4% social services, and 8% no or not known function, whereas 34% of the forest area has multiple purposes (FAO 2005).

1.3 Sustainable management

Effects of human activities on the availability of forest services were limited until 10'000 B.C. since humans were mostly hunters and gatherers, and their impact did not considerably differ from other forest dwellers (Winters 1974, Kimmins 2004). However, technical advances, increased use of forest products and cultivation of forested land for agriculture combined with a steady population growth negatively affected the availability of forest services (Winters 1974). This resource depletion at the local to regional scale also resulted in the formation of a forestry science during the 18^{th} and 19^{th} century in Europe and later in North America and elsewhere (Winters 1974). In the 20^{th} century, number of land uses and thus negative changes in the availability of forest services escalated from local to regional and further to global scales resulting in fundamental concerns about the state and trends of forest ecosystems and the potential threats to the human population (Sharma 1992, Daily 1997, Salim & Ullsten 1999, Woodwell 2001, Millennium Ecosystem Assessment 2005). Net forest area, including both afforestation and deforestation, decreases currently at a rate of 200 km^2 per day, i.e. -7.3 million ha per year (FAO 2006). Yet, regional differences are considerable. Forest area in Europe and especially Asia is presently expanding due to plantations and land use changes, while decreasing rapidly in South America, Africa and to a lesser extent in North and Central America and Oceania. As a result, 8,753 tree species, i.e. about 10% of all trees, are globally listed to be threatened (Oldfield, Lusty & MacKinven 1998). Critical changes in the forest ecosystem are not limited to trees, but include all life forms (Baillie et al. 2004), pools and fluxes (Dixon et al. 1994), as well as interrelated climate (Woodwell 2001). In summary, the number of forest services, and unfortunately at the same time negative effects on their availability, are increasing at an alarming rate (see Kimmins 2004, Salim & Ullsten 1999, Sharma 1992, Woodwell 2001 for an overview).

Sustainable management is the generally agreed approach to maintain forest health and productivity and therefore long term availability of forest services ('forest principles' and 'chapter 11 of Agenda 21' in United Nations 1992, Christensen 1996). Sustainability (World Commission on Environment and Development 1987, United Nations 1992) is a concept that aims at the spatial and temporal balance of ecological, economical and socio-cultural services for current and future human generations. This means that all services have to be available at appropriate levels for current human generations, but at the same time not limiting the potentials for future human generations. As a consequence several administrative processes and meetings have been initiated to formulate criteria and indicators for reaching sustainability in forest ecosystems (FAO 1997); e.g. *Helsinki Process* (European boreal, temperate and Mediterranean-type forests), *Montreal Process* (boreal and temperate forests outside Europe), *Tarapoto Proposal* (tropical Amazon forests), *UNEP/FAO expert meeting* held in Nairobi, Kenya, 1995 (dry-zone sub-Saharan forests), *FAO/UNEP expert meeting* held in Cairo, Egypt, 1996 (dry zone forests in Near East region), or *FAO expert meeting in collaboration with the Central American Commission for Environment and Development* held in Tegucigalpa, Honduras, 1997 (forests in Central America). Hence, a range of ecological, economical and socio-cultural indicators have been formulated that need to be considered equally in order to reach a sustainable management and development of forest ecosystems, and ultimately their availability for human benefit.

1.4 Concepts revisited

Forests are discrete entities of the landscape and form important ecosystems from local to global scales (Fig. 1.1). Forest ecosystems are attributed with a large range of functions. Some of the forest functions are beneficial to humans and subsumed as forest ecosystem services. Each individual forest ecosystem service is important. A sustainable management is therefore required to balance the numerous services in the long term. As a result, the services attributed to the ecosystem have become the target for management activities. It is therefore a generally agreed approach to assess the services as a response variable, and forests as the explanatory variable.

But, many services attributed to forests are not spatially and temporally confined to the forest ecosystem. Some services address only a proportion of the forest ecosystem (e.g. provisioning services), whereas many go beyond forest boundaries (e.g. regulating, cultural or supporting services). As a global matter of fact, 1.4 billion ha, which corresponds to about one-third of total forest or one-tenth of total land area, is considered 'other wooded land' and at least another 76 million ha further 'land with tree cover' (FAO 2006). A considerable amount of natural resources fulfilling the same function as typical forest services are excluded from sustainability

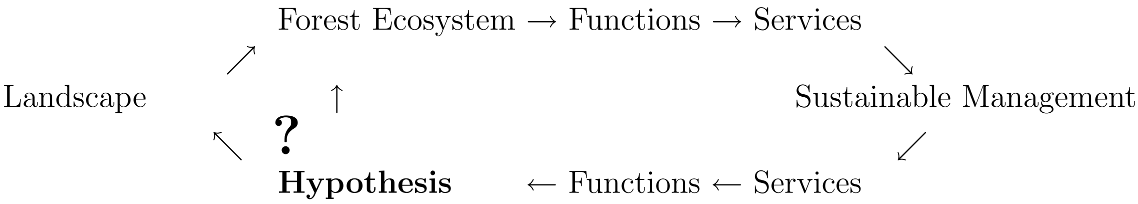

Figure 1.1: Services are typically considered as a function of the forest ecosystem. But the hypothesis states that services are rather a function of the landscape.

assessments. This lack of information has been realised and is now of global concern (FAO 2006).

1.5 Hypothesis and aims

Forest ecosystems are attributed with a considerable number of services that need to be managed in a sustainable manner (Fig. 1.1). However, the reversal of the approach has to be applicable as well. The ecosystem must result as the relevant spatial and temporal domain when targeting the services. The main hypothesis of the thesis is however that the relevant spatial and temporal domains of services do not consistently correspond to forest ecosystem boundaries. State and trends in services are therefore not quantified based on information from the relevant domain. Resulting assessments and monitoring of services may therefore be critically biased when evaluated only within limits of the forest ecosystem. A sustainable management is a priori not possible. And a new conceptual approach in natural resource management is needed to assess, manage and monitor the services in a sustainable manner.

Research aims and corresponding chapters were therefore to

1. ***conceptualise*** an improved approach to assess, manage and monitor forest attributed services based on the entire landscape and not confined on forest ecosystems (Chapter 2),

2. ***evaluate*** the sensitivity of forest ecosystems to underlying ecosystem properties and attributed services (Chapter 3),

3. and consequently ***map land cover variables*** (Chapter 4) and

4. more ***land structure variables*** (Chapter 5) that describe the forest attributed services without suffering from the hypothesised imperfection.

1.6 General study area

The research hypothesis and aims were investigated in western Switzerland mainly based on data from the third Swiss National Forest Inventory (NFI) and the landscape inventory included therein.

Forests in Switzerland dominate many landscapes covering a total area of 1.2 million ha, i.e. 30% of the country's surface (Brassel & Brändli 1999). Forest area per capita is 0.18 ha (Brassel & Brändli 1999), thus lower than global average of 0.62 ha (FAO 2006), but comparable with neighboring Germany 0.13%, Italy 0.15%, Liechtenstein 0.24%, France 0.25% or Austria 0.50% (Brassel & Brändli 1999). Swiss forests range from ca. 200 to 2300 m a.s.l. (Bachofen *et al.*1988) and consist of 46% pure needle leaved, 21% mixed needle leaved, 13% mixed diciduous, and 20% pure deciduous forests (Brassel & Brändli 1999). Dominant tree species within forests (as % of total stem number, but with >10'000 total stem number, according Brassel & Brändli 1999) include *Picea abies* (39.2%), *Fagus sylvatica* (18.3%), *Abies alba* (10.9%), *Larix decidua/kaempferi*$_{exotic}$ (4.4%), *Pinus sylvestris* (3.1%), *Fraxinus excelsior* (3.7%), *Acer pseudoplatanus* (3.5%), *Castanea sativa* (2.7%). Average growing stock of living trees within forest is 362 m^3/ha, which sums up to a total of 417.7 million m^3 in Swiss forests. However, a further 19.7% of total area of Switzerland is land with tree cover outside forests (Brassel & Brändli 1999).

About 20'000 animal species are found within Swiss forests (Meyer & Debrot 1989). At least 36% of total animal and 38% of total plant species depend in some way on forests as their habitat (SAEFL & WSL 2005). More pronounced, roughly half of the birds commonly found in Switzerland use forests on a regular basis, with one third fully depending on forests (Keller & Zbinden 2001).

Services attributed to forests in Switzerland range from timber production, protection against natural hazards, biodiversity, aesthetics to purification of air/water and carbon sequestration (SAEFL & WSL 2005). Sustainable management of these forest ecosystem attributed services is a decicated goal for some time in Switzerland (SAEFL 1997).

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Chapter 2

Forest Services Sustainability

Chapter 3

Forest Ecosystem Sensitivity

Chapter 4

Mapping Land Cover

Chapter 5

Mapping Tree Structure

Chapter 6

Synthesis

6.1 Forest is a dependent management unit

Forests are typically considered as an independent variable that determines the occurrence of ecosystem services and their sustainable management (Kimmins 2004, FAO 2006). Forests are said to provide timber, fiber and food, regulate climate and natural hazards, as well as support the people through nutrient cycling, soil formation and primary production, as well as inspire them culturally and spiritually (FAO 2006, Millennium Ecosystem Assessment 2005). A sound evaluation and monitoring of the services requires that the approach is reversible, i.e. the spatial result of targeting the services in the landscape must be the forest ecosystem. The main hypothesis of this thesis was that the spatial distribution of forest attributed services does explicitly not comply with the forest ecosystem.

Spatial distributions of selected forest attributed services were thus quantified as a function of the entire landscape (Chapter 2). Comparative results confirmed that only economical services were well represented by the forest ecosystem. All other services strongly deviated from the forest ecosystem in their spatial distribution. Large potentials of forest attributed services were found outside forest boundaries. Also temporal changes in forest ecosystems were not consistent with variabilities in attributed services. Thus, the attributed services did not scale consistently with the forest ecosystem.

Also the spatial distribution of the forest ecosystem was quantified by treating forest as an independent variable (Chapter 3). The services are said to depend on the forest ecosystem. Yet, the forest it-self depended on the characterising landscape variables. Forest area in the Jura mountain range changed considerably when varying tree cover thresholds, but was less variable with respect to tree height or stand width. Forest area and distribution thus depended on the characterising variables, and with differing effects. Similar to the services, the forest ecosystem excluded a considerable amount of tree resources. 13.3% of the tree vegetation found in the Jura mountain range was outside forests. As a matter of fact, forests covered 45.2% ±0.4 of the study area even though 73.3% ±0.3 had at least some tree vegetation present. However, this relationship was not necessarily constant between landscapes. As a matter of fact, amount and type of tree vegetation included in forest ecosystems differed between landscapes, despite of the very same ecosystem definition (Chapter 2). In an urban landscape, e.g. canton of Geneva (Chapter 4), the proportion of tree vegetation outside forests was even as high as 47%.

The main hypothesis of the thesis is thus confirmed. A single forest ecosystem does not allow for a consistent quantification and sustainable management of multiple services. As a matter of fact, the forest it-self is a dependent variable. In turn, this dependency between forest ecosystem and characterising landscape variables is determined by the main landscape function (Chapter 2 & 3). Hence, forest is not a land cover, but a land use type.

6.2 Untangling land cover and land use

Land cover is the amount and variability of natural resources in a landscape. In contrast, land use is the function natural resources have for humans and is also referred to as the services. Sustainable management, which takes the actual natural potential into account, requires that the natural resources are quantified as land cover (Chapter 2), irrespective of the land use. However, quantifications of natural resources are often affected by land use and human perception (Nassauer 1995a, Nassauer 1995b). And in turn, the way a manager perceives the resource determines the measures applied for quantification. Results from the regional dependencies of forest services on the forest ecosystem (Chapter 2), as well as from sensitivity assessments on forest characterising variables (Chapter 3), showed that forest is termed as a land cover, but defined and applied as a land use class. Hence, there is a strong relationship between landscape perception and quantification, which resulted in an amalgamation of land use and cover. The aim of quantifying natural resources for a sustainability assessment therefore includes untangling land use from land cover information, i.e. untangling landscape perception from landscape quantification.

Human perception of the landscape was dominated, up to the middle of the 19^{th} century, by impressions from the visible light spectrum received at eye level. Measurements to quantify forest resources were thus confined to these spectral and viewing options available. As a result, forest measures mostly focused on information from single trees accessible from ground; e.g. tree species, basal area, diameter at breast height or single tree height.

The viewing angle for landscape mapping was considerably extended in 1858 by G.F. Tournachon, the first aerial photographer who took a picture from a balloon (Jensen 2000). As a result, a concise view on entire stands and forested landscapes became available. Unfortunately, the spectral information was reduced at the same time since the first photographs were only available in grayscale. Various similar approaches using kites, pigeons or small rockets as vessels followed (Jensen 2000). The first forest related aerial image was documented from 1887 showing a section of Berlin (Hildebrandt 1987). At the beginning of the 20^{th} century aerial photography became operational from airplanes, a technique that was especially advanced during the second world war, and became a standard mapping strategy until today (Jensen 2000). Viewing angle was considerably extended again in the late 1960's when photographs taken on Gemini and Apollo space missions became available (Albertz 1991).

Spectral information for landscape mapping was extended from the visible range with the availability of infrared aerial photographs at the beginning of the 20^{th} century (Wood 1910), but considerably with the launch of the first Landsat mission (ERTS-1) in 1972 carrying the Multispectral Scanner (MSS) on board (Boyd & Danson 2005). A multitude of consecutive sensors followed with increasing spectral resolution to more than 200 narrow bands, what is today known as hyperspectral data (Boyd & Danson 2005, CEOS 2005). In parallel to these optical and passive sensors, a suite of active sensors ranging from SAR to laserscanning was developed that offered additional information on the geometric surface properties of the landscape. The spectral range and resolution was continuously increased, which lead to a large number of applications (Van der Meer & De Jong 2001, Schaepman 2006). These applications and underlying concepts were only possible with the advancement of remote sensing techniques and consequent broadening of the perceptional horizon.

A positive feedback system thus exists between methodological advances in remote sensing, landscape perception, concepts and measurements. In this thesis, an existing landscape perception was challenged and replaced by a new gradient concept (Chapter 2 & 3). The concept required new measures of continuous fields in land cover, which were promisingly realised based on spectral information from remotely sensed Landsat 5 TM data combined with generalised linear models (Chapter 4). The approach was only limited by the ability to account for the vertical distribution of continuous fields. Mapping performance of fractional tree cover was strongly affected by the vertical structuring of the vegetation, i.e. mean height of tree canopy cover and associated leaf area index. One solution to compensate for this vertical effect is to use active sensor data that is not susceptible to vertical effects, or more specifically has its strength in the assessment of vertical structure such as first-/last-pulse or full-waveform laserscanning (Chapter 5). Another solution, that I plea for, is a continuation of the elaborated feedback system between concepts and methods in the sense that the observed remote sensing deficiencies should promote our landscape perception and ultimately advances our concepts. Current landscape ecological approaches mainly address the horizontal distribution of natural resources. However, a sound conceptual and methodological inclusion of the vertical distribution is barely available in landscape ecology or remote sensing, but definitely required for natural resource management: grasses overgrown by trees are addressed as trees, an underground parking as vegetated, a planted roof as a grasses, a glacier floating over rock as ice. Further conceptual research is thus needed to translate the continuous hyperspace approach from a two- (spatial surface) to a three- (height), and possibly four-dimensional (time) hyperspace. It is essential that technical advances in remote sensing promote new landscape perceptions and concepts, and do not try to imitate former conceptual approaches. At the same time, landscape perception needs to conceptually extend its range and acknowledge the variable space that is not directly accessible through the human eye, especially since visual appearance ultimately drives the planning and management (Nassauer 1992).

To conclude, remote sensing data is sensitive to land cover, but insensitive to land use. Remote sensing is therefore not only an efficient mapping methodology (Chapter 4 & 5), but more so a consistent indicator to evaluate if land cover is treated separately from land use, which is a generally complex task (Jax 2002). As an example from this thesis, sensitivity analyses on forest services and the ecosystem proved a misconception (Chapter 2 & 3) that could have been revealed much earlier when conceptually analysing and improving the errors of commission in former remote sensing based forest classifications. Burned, cut or damaged forest areas contain no or only few trees, but are still considered forest. From a spectral point of view, such areas do not differ from e.g. grasslands or bare areas. This leads to the hypothesis that forest is a land use type that by definition cannot be mapped consistently using remote sensing data. In contrast, fractional tree cover is a land cover variable and thus resulted in more robust mapping results (Chapter 4), and revealed major differences to forest distributions (Chapter 5). Hence, remote sensing has proved to be an efficient mapping tool. But, remote sensing might be even more valuable for a consistent conceptualisation of a sustainable management and monitoring system of natural resources.

6.3 Natural resource management for sustainable development

Forests are perceived as land cover. But, results from this thesis showed that forests are defined and applied as land use. Confounding effects in the management of natural resources between land use and land cover impede a sustainable development (Chapter 2). I therefore propose a natural resource management system that conceptually and methodologically separates land cover from land use (Fig. 6.1).

Land cover addresses the physical presence of natural resources in the landscape. Land cover thus represents the availability of services and, concluding from the findings in this thesis (Chapter 2), needs to be quantified based on the gradient concept (Keane et al. 2002). Also the monitoring of services needs to follow the gradient concept, so that the entire natural potential of a landscape is included (see discussion and conclusions of chapter 2), which is markedly different to the actual landscape in Switzerland (Brzeziecki et al. 1993).

Land use addresses the functions of the landscape that are beneficial to humans. Use of natural resources creates a demand that needs to be managed. Management of demands on natural resources essentially means an appropriate planning of the landscape. Land use planning addresses discrete sections of the landscape. Here, the ecosystem is an appropriate concept to plan, manage and intervene natural resources because it integrates biotic and abiotic systems that are focused on defined target functions.

Services represent the conceptual link between land cover and land use. Land cover corresponds to the availability of a natural resource, while land use describes the way humans take advantage of the natural resource (Fig. 6.2). Thus, a service basically describes the human use of a natural resource based on its actual availability. Land use affects the availability of a resource and results in a lower actual than

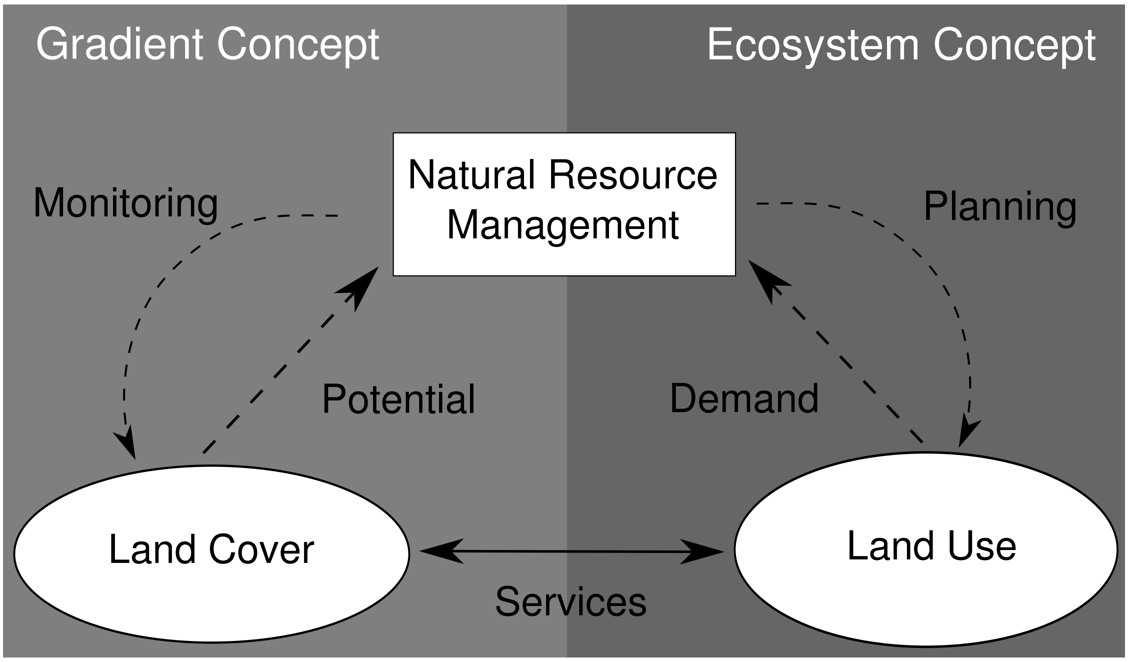

Figure 6.1: Natural resource management balances land use demands with land cover potentials through planning and monitoring. The services represent the conceptual link between land cover and use.

potential service performance (Chapter 2 and Fig. 6.2). This difference between actual and potential performance of a service represents a measure for the sustainable state and trend of a service. As a consequence, natural resource monitoring needs to focus on the area under the density curve for the actual and potential performance of services (Fig. 6.2). In this approach, natural resource management and monitoring is thus inherently a spatially and temporally dynamic system. Range limits are especially sensitive to sustainability evaluations as they indicate for changes in the potential performance of a service and thus a fundamental change in the availability of a service in the landscape.

Natural resource management for a sustainable development thus requires both the ecosystem approach for planning and the gradient approach for monitoring. Application of the ecosystem approach is well established (Grumbine 1994, Christensen et al. 1996). And application of the gradient approach (Gleason 1926, Whittaker 1956, Austin & Smith 1989, Keane et al. 2002) is further elaborated in this thesis. However, much conceptual and methodological research is needed on how to transfer the results between the two approaches for an iteratively sustainable development. Conceptually, continuous land cover information is contrasted with discrete land use classes. Methodologically, continuous raster data is contrasted with discrete vector data (Wicks et al. 2002). Above all, thresholds for potential concerns need to be defined on when and how land use classes, i.e. ecosystem definitions, need to be adapted because of critical changes in continuous land cover.

Scale is a particular attribute of the proposed natural resource management

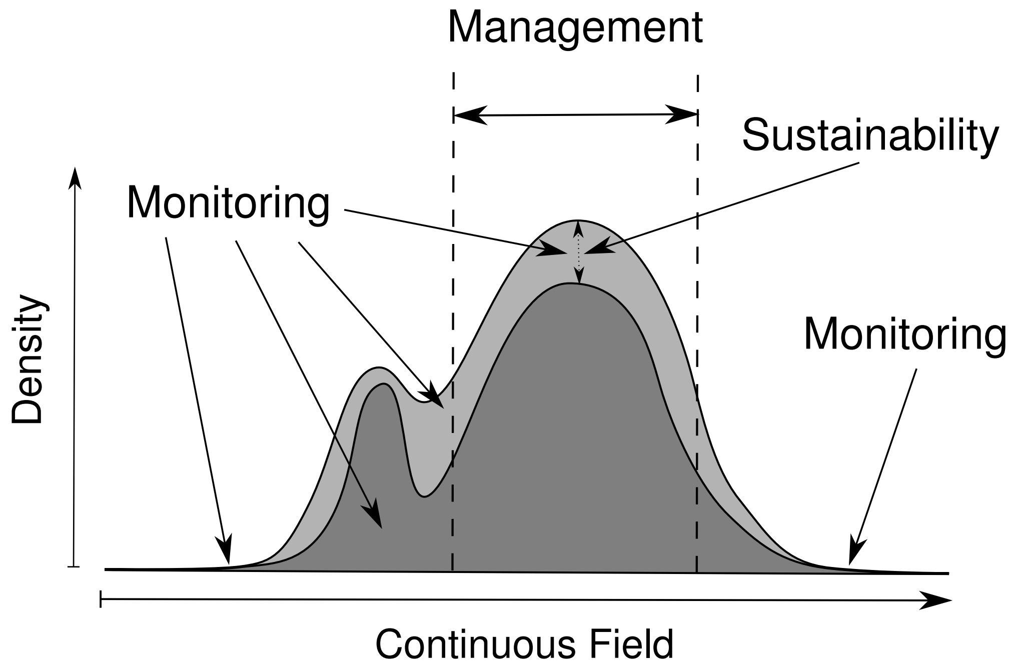

Figure 6.2: Actual (dark gray area) and potential (dark & light gray area) performance of a service along a continuous field. Management of natural resources follows the discrete ecosystem concept and focuses on the core area. Monitoring of natural resources follows the gradient concept and focuses both on the area under the density curve and the sensitive outer transition zones. The deficiency between potential and actual performance (light gray area) corresponds to the sustainability measure of a service.

concept. This thesis addressed the spatial landscape scale for a maximum of two temporal time steps. However, both the ecosystem (O'Neill et al. 1986, Levin 1998) and gradient concept (Keane et al. 2002) are embedded in a hierarchical framework along scales (Allen & Starr 1982, Urban et al. 1987). As a matter of fact, the gradient approach contains the hierarchy inherently as a gradient at the level of focus is based on a discretisation on the level just below (continuous tree vegetation at the landscape requires definition of a tree at the local scale). Downscaling of forest properties to the tree and leave level, as well as upscaling to the regional and global level is thus indispensable (Sexton et al. 1998, Wu 1999). As a consequence, also the remote sensing methods need to reflect these different scales. Scale specific sensors are available ranging from a combination of terrestrial laserscanning and spectrometers at the local to airborne digital multi- to hyperspectral cameras and laserscanners at the landscape and multispectral spaceborne sensors and radar at the regional scale. Too often however, the methods are confounded and therefore loose some of their mapping power. A clear focus on a specific scale must stand at the beginning of a management and monitoring activity, also from the methodological point of view. However, further research is needed to transfer methods and mapping results between sensors along the scale ladder.

In final conclusion, natural resource management serves a sustainable development when land cover and use are balanced conceptually and methodologically along multiple scales in space, time, and ecological hierarchy.

6.4 References

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