A South Korean case study of social-ecologically-based management of ecosystem services: Global change impacts on agricultural production versus water quality in mountain landscapes

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Abstract: As a case study where management based on social-ecological principles should lead to sustainable supply of ecosystem services, the international project TERRECO (Complex Terrain and Ecological Heterogeneity) applies a transdisciplinary modelling approach to examine current and potential future natural resource use within the largest reservoir system of South Korea, Soyang Lake Watershed. Due to intensive fertilization, small catchments within the watershed export some of the world's highest levels for N and P, while steep terrain and monsoon rains result in extremely high material transport. To consider future management with climate change at regional scale, new integrated modelling approaches are being developed for land surface processes and production, for hydrology and transport, for economic evaluation of ecosystem services, and for associated management and decision-making. The models are supported by ground-based studies of ecosystem physiology and agricultural yield, of soil properties and erosion, of stream flows and transport, of groundwater exchange, of farm economic balances, of statistical data bases, and of individuals preferences in decision-making within particular regulatory and economic frameworks. Scenario evaluations are planned in partnership with provincial and national agencies that currently carry out land use planning and advise on policy making. A common interest among project participants and agency planners focuses on scenarios examining sustainability of ecosystem services. The required transdisciplinary integration for assess-ments of alternative futures, drives the development of modelling systems that apply at landscape to regional

scales, couple to specific conceptual goals, and should provide for communication on uncertainties with managers and stakeholders.

Keywords: landscape models; agricultural production; water quality; social-ecological scenarios; agency discourse; sustainability; ecosystem services; mountains

1. The landscape scale research challenge due to global change

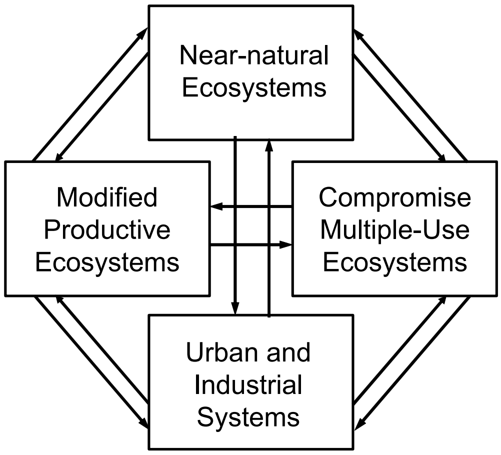

Figure 1. Categories of ecosystems determining landscape-level processes. Modified from Odum (1985).

During recent decades, anthropogenic impacts on natural and managed ecosystems have increased to alarming levels (Alcamo *et al.* 2003, 2005). Climate change due to increasing atmospheric carbon dioxide concentration is altering the radiation input, temperature regime, and precipitation regime of ecosystems, and will, thus, shift both water balances and production (Kabat *et al.* 2004, Canadell *et al.* 2007). Atmospheric deposition (Schulze *et al.* 1989) and intensive land use with high levels of fertilization (Vitousek *et al.* 1997) have modified plant growth, nutritional balances of ecosystems, nutrient losses to aquatic systems, susceptibility of organisms to disease, composition of communities, and ecosystem resistance to stress. These modifications in ecosystem function affect derived ecosystem services, i.e., agricultural and forest products, water discharge into rivers and streams, water quality, and biodiversity.

Global change and its related suite of environmental problems have resulted from mankind's increasing capacity to impact biogeochemical cycles, the land surface and biodiversity at global scale (Alcamo et al. 2003, 2005). The need to recognize the significance of *Man* as an ecological factor and to link management of natural ecosystems with those modified by *Man* has been an issue in ecosystem science for more than half a century (Fig. 1; Odum 1985). But the study of social systems has not yet become a fully integrated component in ecology and environmental sciences. Davidson-Hunt and Berkes (2003) summarize the state of affairs in the following way:

> *"With the Age of Enlightenment humans were extracted from the environment. The separation of nature and society became a foundational principle of Western thought and provided the organizational structure for academic departments. Since that time, Western thought has oscillated between positions in which nature and society were treated as distinct entities, and one in which articulations between the two were examined."*

Complex interactions of atmospheric, biological, geochemical, and hydrological factors together with decision-making and management determine the dynamics of landscape water, carbon, and nitrogen cycles important to mankind's well-being. Due to the complexity of landscape response to atmospheric deposition, altered climate, and land use change, sustainable use of natural resources requires a new understanding of how energy and water budgets, the carbon cycle, and nutrient cycles are coupled (Tenhunen and Kabat 1999). Experimental projects and models must be designed to achieve a synthetic understanding of ecosystem processes and their variation at the stand level. But validated simulation models must also provide information on how to maintain appropriate levels of production, adequate water discharge from watersheds, and acceptable water quality, e.g., suitable integrated function of ecosystems at landscape scale. Additionally, our regulatory choices and actions and their consequences must be made clear. Thus, new tools must be developed that help us to understand the consequences of human decision-making with respect to ecosystem performance.

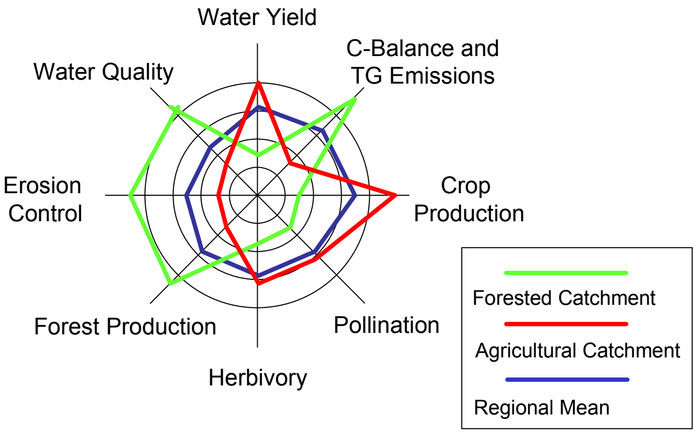

Figure 2. Schematic illustration of possible trade-offs in ecosystem services obtained from landscapes dominated by forest (green line) or intensive agriculture (red line), as well as the average land use across a region (blue line).

We are challenged to practically apply spatial models at larger scales where they should provide evaluations in terms of concretely defined services. For example, we might consider the flow of water via alternative pathways through different types of landscapes. Depending on climate and land use characteristics, we expect negative influences of agricultural intensification on the yield of high quality water to reservoirs and to the drinking water supply, while at the same time, agricultural products represent a gain in services. In the context of this trade-off, spatial simulation models should provide us with estimates for a variety of important services as illustrated in Fig. 2. Water yield, water quality, soil erosion, plant production, landscape carbon balance and emissions are ecosystem services that we must quantify, and then ultimately express in economic terms, in order to link with the social system. In this way, it is possible to examine profits achieved versus costs that are incurred in selected landscapes and regions (*sensu* Crissman et al. 1998).

Thus, environmental scientists must now work to bridge between studies that determine spatial patterns in ecosystem performance, the supply of ecosystem services from landscapes and regions, and social system use of these resources as well as management measures that feedback on future land use. Coordinated assessment frameworks are needed for landscape to regional scale applications that quantify trade-offs in services gained (or lost) in response to management decisions. These assessment frameworks must allow us to determine how shifts in climate, in extreme climate events, in land use and in social response to global change pressures influence landscape performance and, therefore, potentially derived services. Ultimately we also want to know whether adaptive measures in management may be carried out to reduce risk. The preference for carrying out such modelling at landscape to regional scales relates to the need to work with locally appropriate data, local integrative measures (e.g., ecohydrological parameters and remote sensing), to focus on locally important specific environmental problems, to serve particular stakeholder groups, and to conduct analyses appropriate for the confronted cultural and social context. The required transdisciplinary integration for assessments of alternative futures (e.g, research strategies that cross many disciplinary boundaries to create a holistic approach; cf. Hulse et al. 2004, 2008 and definitions in Wikipedia) must drive the development of modelling systems that apply at landscape to regional scales, couple to specific conceptual goals, and provide for communication on uncertainties with managers and stakeholders (Liu et al. 2008, Carpenter et al. 2009).

2. The TERRECO project case study in complex terrain

Complex terrain refers to irregular surface properties of the earth that influence gradients in climate, transfer of materials, soils properties, selection of organisms, and via human preferences, the patterning of land use. Complex terrain of mountainous areas represents ca. 20% of the Earth's terrestrial surface; and such regions provide fresh water to at least half of humankind (Mountain Agenda 1998). There is a need to quantitatively understand the ecosystem services derived in regions of complex terrain, the process regulation occurring to maintain those services, and their sensitivities to changes in climate and land use.

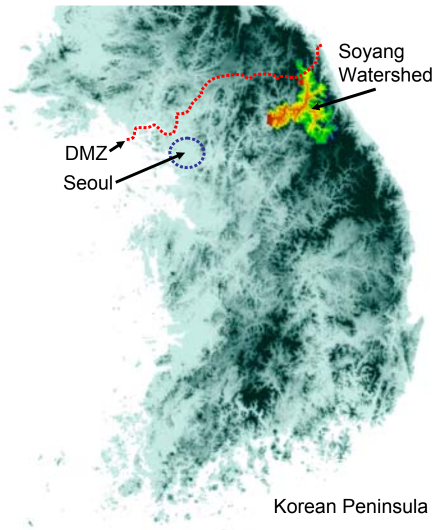

Figure 3. Location of the study site.

The international consortium project TERRECO (Complex Terrain and Ecological Heterogeneity) focuses on building a bridge between spatial patterns of ecosystem performance in complex terrain of the Soyang Lake Watershed, the largest reservoir system in South Korea (Fig. 3), and derived ecosystem services. Extremely high applications of synthetic nitrogen fertilizers in dryland farm fields, import of manure for organic farms, the expanded planting of legume crops, and the probable significant deposition of nitrogen-containing air pollutants lead to high N inputs to mountainous landscapes in Korea (Jung et al. 2009). The increased N availability permits increases in food production, which includes summer vegetable production from highland agriculture for the population centers, but with increased emissions of green-house gases and high levels of catchment nitrogen exports that decrease overall ecosystem services by decreasing freshwater quality in major reservoirs. Overall landscape and regional N balances, and in this context the uptake of N by crops produced, denitrification in wetlands or rice paddies, total greenhouse gas emissions, and the proportion of N exported to reservoirs have only partly been described to date. As found in global trends, phosphorus is also accumulating in Korean landscapes through fertilization, especially application of animal manure. Monsoon rains together with prevailing dryland farming practices on steep slopes lead to large sediment loads and export of total P to the same reservoirs. Several small catchments within the watershed export some of the world's highest recorded levels for N and P (Kim, B., Kangwon National University, personal communication). High background levels of N provide for high potential algal growth, algal blooms and eutrophication in response to monsoon-rain-based pulses of P.

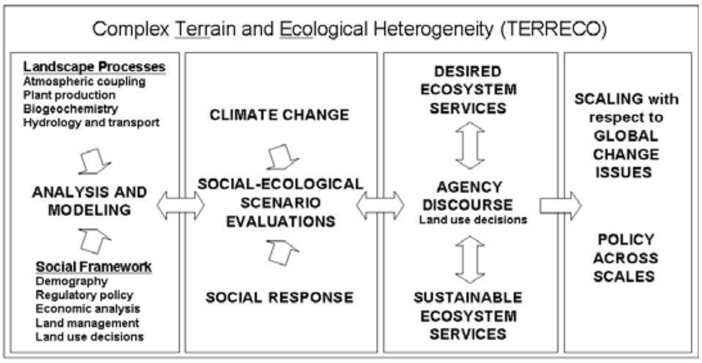

Figure 4. Information flows and bridging undertaken and planned within the TERRECO project which examines trade-offs in agricultural production versus water quality and water yield in the Soyang Lake Watershed of Kangwon Province in South Korea.

TERRECO as a consortium project pools expertise from four universities (Kangwon National University, Seoul National University, Yonsei University and University of Bayreuth) to examine current, and to address potential future natural resource use within the Soyang Lake Watershed. TERRECO applies a transdisciplinary approach (Fig. 4 left panel) to first develop simulation models for landscape processes within the framework of current management practices and as influenced by current regulatory policies. Via this suite of spatially compatible models, the abiotic and biotic studies of soil processes, hydrology and water yield, material transport and water quality, agricultural and forest production, and production-related biodiversity in complex terrain are merged. In addition, the socio-economic background of current land use is analysed (Fig. 4 lower left panel). The economic gains from production as well as costs due to erosion and water reclamation are included into a sector model adjusted to the Soyang Lake Watershed, which encompasses four counties in Gangwon Province. The current decision-making of farmers and their orientation to policy measures must be understood. Overall, the degree of flexibility available for influence by management measures must be assessed (see also section 4 below).

The goal of work depicted in the left panel of Fig. 4 is to build capacity, that will support in a subsequent phase, the evaluation of social-ecologically-based scenarios. Design of the scenarios depends on an in-depth understanding of potential climate change, potential social response, the goals set by planning agencies, and the capabilities of the landscape models. Thus, model designs must be developed to the best of our ability to include sensitivities for projected climate change, but also to consider potential social response to climate change, e.g., altered land use depending on possible future regulatory regimes and economic conditions. Viewed in this context, it is clear that a project such as TERRECO faces from the beginning an overwhelming complexity. However, we can attempt to reduce this complexity stepwise via discourse with agencies and stakeholders, dedicating our analytical capacities to the most important issues. A phrase which is recently often heard, namely “learning-by-doing” becomes clear in this context, and it is an essential component of the work. Models for social-ecological system analysis must, on the one hand, be based on existing tools and experience, but they must have capacity for flexibility and evolution that is required as our experience with “system complexity” grows.

In summary, this case study attempts to quantify potential gains or losses in ecosystem services associated with the general threats posed by altered nutrient cycles and biogeochemistry occurring under global change at local, landscape and regional scales. To consider alternative future management, integrated modelling approaches are required for land surface processes and production, for hydrological phenomena and transport, for economic evaluation of ecosystem services, and for management and decision-making within the social context of South Korea. It is hoped that the research effort will demonstrate management principles that contribute to sustainable resource use both in Korea and at other locations worldwide.

3. Process models and supporting data within TERRECO

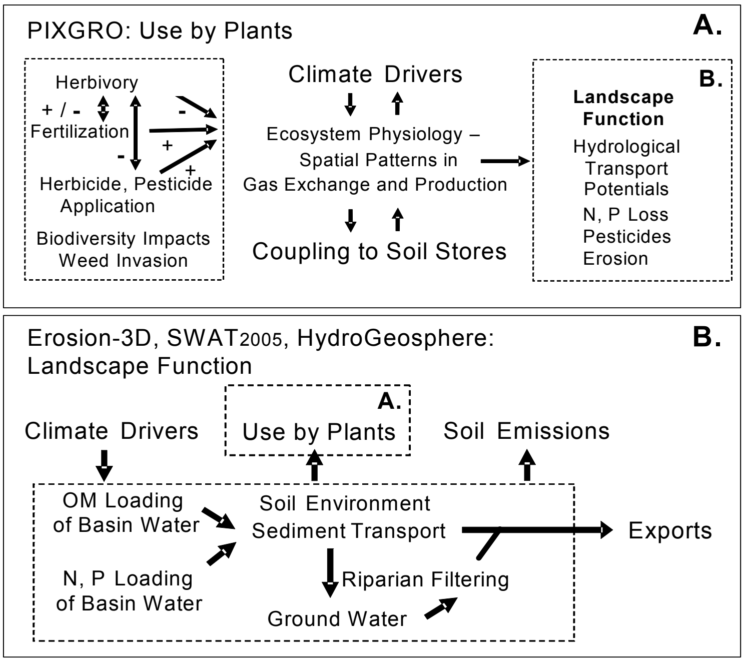

Figure 5. Visualized linkages in models A. Land surface processes and water use by plants. B. Hydrology and biogeochemistry.

Research themes during the initial phase of TERRECO focus on the first two boxes at the left in Fig. 4, working to design efficient and compatible modeling tools, as well as the required spatial data bases to support them, and to design scenarios that examine future resource use. A joint program of biophysical and socio-economic monitoring is being undertaken together with Korean institutions and agencies to consolidate current scientific understanding of global change, to identify critical system variables and indicators, and to ensure that modeling tools are capable of projecting the results of likely change.

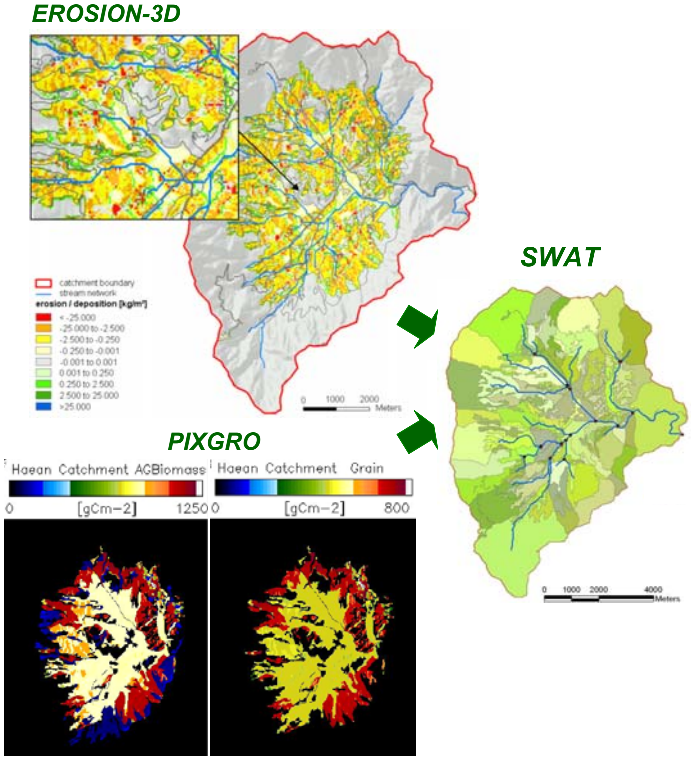

Figure 6. Partial conceptualization of the production-hydrological framework of TERRECO as described in the text.

Process model development is oriented to the two foci illustrated in Fig. 5A and 5B. An adapted version of the PIXGRO model (Fig. 5A; Tenhunen et al. 2009) builds the linkage between land surface exchange, ecosystem carbon fixation, allocation and growth, and crop yields. Challenges relate to including sensitivities with respect to management measures that determine influences of herbivory and weed competition on yield (see also discussion in section 4). PIXGRO is sensitive to and modifies soil nutrient and water stores, and in this manner is coupled and should exchange information with models of Landscape Function (Fig. 5B).

Several established models provide prototypes to estimate agricultural and climate effects on basin exports (e.g., Erosion-3D, SWAT2005, and Hydro-Geosphere; Fig 5 and 6). Of particular importance is the development of potentials to analyze land use management as it may improve nutrient retention, reduce erosion, and improve ground water quality.

Landscape processes of course influence the function of ecosystems as well as spatial patterning in greenhouse gas emissions (coupling in Fig. 5A and 5B). The conceptual scheme for an overall production-hydrological framework (Fig. 6) indicates that various modeling approaches are applied to examine disciplinary questions and/or to determine simplified descriptions of ecosystem services at landscape scale.

The process modelling is supported by three ground-based studies at intensive research sites that provide information on process interactions and validation data. The first is a spatially-distributed design for examination of ecosystem physiology, production and landscape structure influences (e.g., forest/field distribution) on biodiversity (herbivores and weeds) and biodiversity impacts. The second is an intensive sub-catchment study of dynamic changes in surface flows, bio-geochemistry and ground water movement, together with a larger monitoring network of ground water wells and surface fluxes. The third experimental approach is an evaluation of the influence of soil amendments in the form of polyacrylamide (PAM) and/or charred biomass (CB) on ecosystem processes and transport in runoff plots. The experimental studies are located on differing slopes and if possible near the stream and along the pathway of flow within the sub-catchment experiment from forests to dryland fields, and then to rice paddies in the basin.

4. Linking of process model results to the social system

As illustrated in Fig. 4, modeling approaches are required to relate natural processes to the social framework, especially since this determines land use. An initial step is to evaluate the outputs of natural science models in economic terms, since economy is strongly tied to environmental policy and decision-making. Thus, the yield outputs from PIXGRO, which has capacity to respond to climate change influences, should provide inputs to an agricultural sector model (ASM; Fig. 7). Nevertheless, this critical linkage is still in development and is burdened by the need on the economic side to include many crops. A partial solution to this problem may be to develop PIXGRO for as many as 10 functional vegetation and crop types (thus including climate and management sensitivities), and then to extend the results of simulations based on statistical comparisons of crops within a group. Another problem to be overcome is that the concepts for yield in PIXGRO and the ASM are extremely different and must be reconciled in some way as the limitations of each model become defined. As another alternative, a Hierarchical Bayesian Model (HBM) is also planned for crop yields that includes concepts and information from physiological crop models, from long-term statistical data on yields, and from long-term climate; and where results are projected along climate gradients onto maps developed at Soyang Lake Watershed. Bayesian concepts should simplify the integration of natural science based simulations with available statistical data and information from independent crop studies, allowing us to maintain consistency in results that are based on information from different sources. In any case, the yield models must allow us to predict crop production as carried out in real landscapes, in agreement with published agricultural studies in Korea and with confidence that they are applicable to situations with altered climate; equally so, they must be compatible with an economic world view. Helpful guiding investigations have been published over large areas within Japan for rice yield by Izumi et al. (2009) and in China for maize production by Tao et al. (2009).

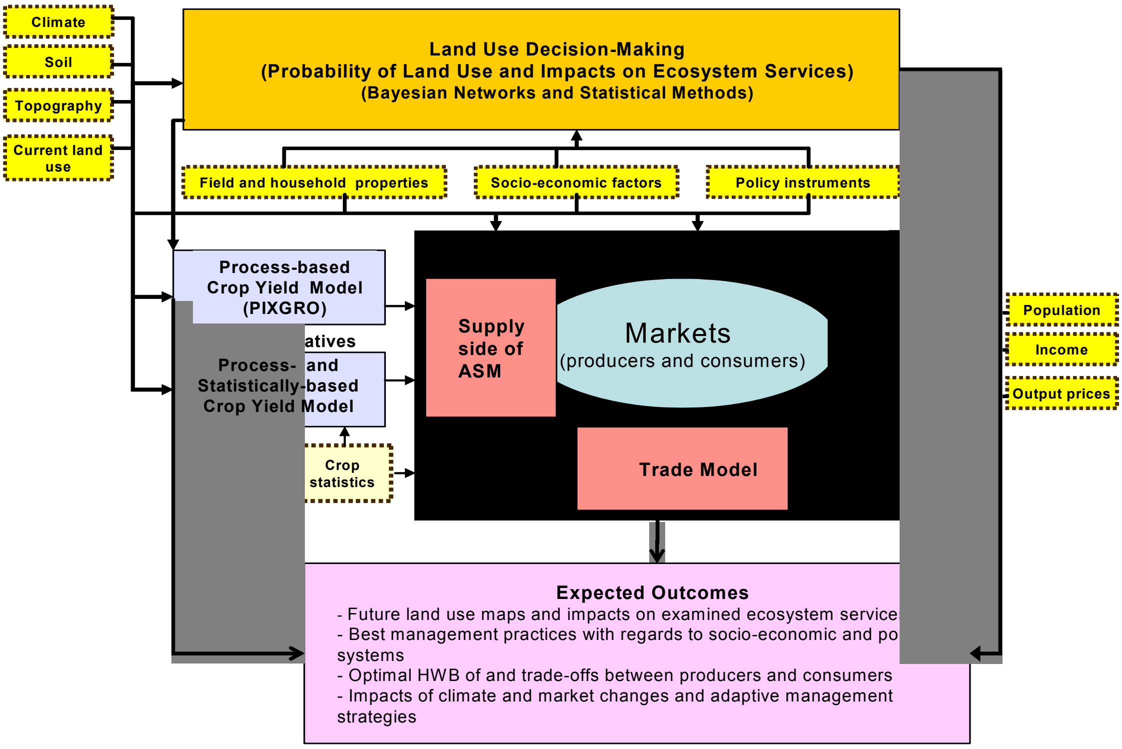

Figure 7. Conceptual coupling between the TERRECO production, Agricultural Sector, and land use decision-making models. Relationships to data bases are also indicated.

The ASM includes three different modules: supply, demand, and trade. With regard to the supply, agricultural production depends on many factors that could be categorized into three groups, namely biophysical (soil type, nutrient availability, climate factors, and water availability; e.g., factors discussed for the yield model above), socio-economic (technology, resource endowment, management capability, and markets), and policy (taxes, subsidies, quotas, etc*)* factors. Demand includes consumption, industrial use, and feed for animals. The difference between supply and demand is compensated by trade, either domestic or international import and export. Domestic trade is considered to be free but international trade is subject to tariff and non-tariff constraints. An extremely important component in development examines ways to include erosion and water reclamation as production costs in the economic analysis (cf. Mimouni et al. 2000; not depicted in Fig. 7).

The expected outputs of the ASM should be: (1) The estimates of agricultural supply under resource constraints (land, labor, capital), (2) the projections of agricultural production, adjusting the potentials obtained from the natural science-based yield models, projections of consumption, and with subsequent development (3) the stimulated changes of agricultural production and consumption, and of human well-being of producers and consumers under different relevant scenarios. Specific considerations under study include the changes of agricultural production technology (e.g. the conversion from conventional to organic farming) and the labor market as well as payments for environmental services in terms of government subsidies (over the long-term including costs due to erosion and water reclamation).

Additionally, however, the transformation of natural resources into goods or services is not only governed by ecosystem processes and economics, but also strongly by concerns most often addressed today as social science themes; namely, environmental perception, knowledge and available technology, the political framework, and environmental policies. In TERRECO, we have only made a first step to date in our planning to couple ecosystem response and economic gains (and/or losses) to agricultural land-use decisions. A model is being constructed to incorporate social, economic and ecological considerations of local actors (e.g., the farming communities; Fig. 7). The scientific framework for agricultural land use decision-making is adapted from the 'Theory of planned behavior' by Ajzen (1991), which assumes human decision-making to be based on i) cost-benefit expectations, ii) subjective norms, and iii) perceived behavioral control. Additional conceptual work is required.

Conclusion

Solving of problems in the environmental sciences that result due to the activity of *Man*, e.g., due to global change, or the adaptation of social-ecological systems in the context of global change require new modelling methods with a clear focus on well-specified questions and in a defined cultural and social context. In order to work toward sustainable management, transdisciplinary integration is needed in modelling to assess as well as possible the consequences of policy decisions as they determine "alternative futures" in land use (Rapport et al. 1998), and thereby ecosystem services. Setting of these types of goals influences both scales and methods that are used in models. The complexity and data needs of transdisciplinary integration forces a selection of scale to regions that are homogeneous with respect to factors important to response of both the natural and social systems. The need to reduce complexity encourages us to develop new partnerships between academic institutions, management agencies, and stakeholders. These in turn will influence the design of required modelling systems. In general, we can conclude that many "off the shelf" modelling methods, while offering prototype methodologies, are inadequate to meet the new challenge. Modelling systems must now be designed with flexibility and must evolve as new insight is gained to the social-ecological system under study.

Within the TERRECO project, water and alternative pathways of water use provide the medium that links *Man* and nature within an evolving social-ecological system and with land use decision-making. The overall goals as depicted in Fig. 8 are quite general, and relate to scenario evaluations that include change in both climate and social factors that influence policies and land use. The methods, however, are in the process of being adapted to the highland agricultural systems of Soyang Lake Watershed. The focus on trade-offs in agricultural production versus maintenance of water quality determine the emphasis and investments in model development. A general framework has been designed (cf. Figs. 5, 6 and 7; sections 3 and 4), but PIXGRO, Erosion-3D, Hydro-Geosphere, and $SWAT_{2005}$ must adapted to the results of field studies and in relation to expected climate change. The projections of future land use must go beyond considering the response of local actors and must include integrated social-ecological approaches that consider the prevailing regulatory regime and the prevailing economic framework together with nature perception at different scales (Fig. 8).

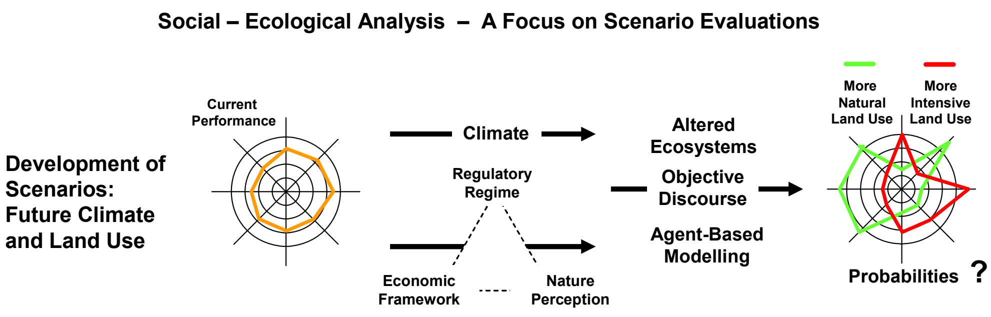

Figure 8. Natural and social science parallel analysis of social-ecological systems planned in TERRECO, which lead to "alternative futures" scenario development with respect to ecosystem services.

Additionally, a project partnership is currently being built with agencies that have the mission to carry out land use planning and to advise in policy making. A common interest is found among TERRECO project participants and agency planners in evaluating scenarios to quantify the effects of land use decisions in compliance with stakeholder demands. A second common interest is visualized in considering land use management that may contribute to sustainable gains in ecosystem services. Thus, much work remains not only in development of the needed modeling tools, but also in the informed formulation of scenarios that are useful in planning of future resource use.

Viewed more generally, the prevalent methodology and response to environmental problems promoted by current institutional structures has been to treat the symptoms of the problem, with an intention to either conserve or return observed systems to a previously attained and desirable state, most often considered from the standpoint of a single discipline. In this case, conventional modelling approaches have been applied, most often within a single discipline. However, the synthetic social-ecological approach described above based on complex scenario development is compatible with the vision of Holling (2001) that foresees cycles of "adaptive renewal" in the world around us. Holling emphasizes the importance of potential reorganization of social-ecological systems after disturbance, e.g., after a transition to an undesirable state due to global change. To consider potential reorganization and new choices in terms of desired future alternatives, *Man* cannot be treated in the sense of a climate variable that simply influences the system, rather human behavior must be integrated into the system and be considered with respect to determining future land and resource use trajectories. Viewed positively, environmental problem solving should capitalize on the reorganization potential of social-ecological systems (Berkes et al. 2003). Thus, recommendations have been made that problems related to resource management and global change should be treated in the context of a new paradigm in design of institutions and management measures (Table 1; Pahl-Wostl 2007). Resulting changes would strongly support new dynamic interactions between environmental scientists and management agencies, making the need for transdisciplinary modelling approaches essential.

The goal of resource management is to achieve sustainable outputs of goods and services from ecosystems in order to support human well-being. Derived ecosystem services depend on climate and land use, but also on environmental policy determined by the existing regulatory regime. In addition, cultural perceptions, economics and available technology ultimately influence the decisions in resource and land use made by individuals (Fig. 8). Current environmental problems that modify ecosystem services arise due to changes in these factors which are due to human impacts on the biosphere, e.g., global change. Problem solving in the context of global change requires that adaptive management with an awareness of social-ecological complexity be carried out that "management practitioners" are provided with information about the potential effects of global change that may occur due to both climate and human decision-making. With the availability of such information, the best ways to tune environmental policy may be sought, ensuring compatibility with stakeholder interests, capitalizing on capacities for social-ecological system reorganization, and working toward sustainability in resource utilization. All of this requires new modelling approaches for land use systems at landscape and regional scales.

Table 1. Characterization of current "Business as Usual" and desired "New Paradigm" regimes for resource management, extending ideas on adaptive management through social learning described by Pahl-Wostl et al. (2007).

	Business as Usual: Prediction and control	**New Paradigm Orientation: Integrated adaptive regime**
Decision-Making and Policy Structure (adapted from Pahl-Wostl et al. 2007)	Centralized hierarchical governance	Polycentric and "horizontal" structure in governance
	Narrow or no stakeholder participation	Broad stakeholder participation
	Separate sector analyses leading to policy conflicts	Cross-sectoral analysis and integrated policy implementation
	Single scale focus and analysis	Multiple scale analysis
	Fragmented understanding and proprietary information	Comprehensive understanding and integration of information
	Centralized infrastructure	Decentralized infrastructure
Required Educational Support Structure	Disciplinary science	***Transdisciplinary education***
	Exposure to model evaluations	***Broad training in modelling***
	Examination of sensitivities to limited driver variables	***Complex scenario development and study***

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