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Realizing Transition Pathways to Provide Required Ecosystem Services – an Inverse Approach

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Abstract: In this study we propose an inverse model approach to quantify the required ecosystem services provision to achieve future planning goals. As a case study we investigate urbanization processes in two regions in Switzerland. We use a binary logistic econometric model to relate probabilities of urbanization to a set of land use determinants such as geographical factors, climate, agricultural subsidies, and ecosystem services. By the use of the inverse modeling we find the necessary trade-offs between ecosystem services in order to achieve a given probability of land use change from agricultural to settlement. From an urban planning perspective such *given probability* corresponds to a given or desired future urbanization level, which, in turn, is defined by stakeholders. Of particular interest for planners is the trade-off analysis between ecosystem services because it provides a number of transition pathways to achieve future planning decisions in a sustainable manner. In this way, once a future planning scenario is defined, future demands for ecosystem services under such scenario can be derived from the inverse modeling. Additionally, results of this contribution reveal for the study area that ecosystem services seem not have been included in spatial planning decisions. For this reason, in the conclusion section we encourage and recommend planners and stakeholders in general to not only focus further research on understanding the importance of ecosystem services in urban and landscape systems, but also to incorporate that knowledge in the planning decisions.

Keywords: Inverse modeling; ecosystem services; trade-offs.

1 INTRODUCTION

Human activities and consequential global climate change are increasingly jeopardizing the ability of ecosystems to provide essential services for human livelihoods (UNFAO, 1996; Gleick,1998; Hoffert et al., 1998). Past and current policy strategies have not managed to mitigate the impacts of these trends yet, calling for more disruptive changes in society and in ecosystem management based on a sound understanding of the requirements for adequate ecosystem services (ES) functioning (Gretchen, 2000)

Traditional forecasting approaches are based on dominant trends and are therefore unlikely to generate novel solutions. In contrast, inverse modeling approaches are based on articulating tolerable futures first, and using them as a guide for designing and implementing measures that facilitate the transition towards these futures in a later step. The essence behind the approach is that our perception of what is possible or reasonable may be a major obstacle to real change. In this contribution, we aim at introducing this new approach for realizing a transition pathway to provide required land uses and their related ES, where the point of departure is not current data, but a future desired by stakeholders. Based on a defined land use changes, we subsequently infer the amount of agriculture subsidies and the trade-offs between ES to bring about this change. We will especially show, how such an approach can improve the understanding of the ES trade-offs involved in the realization of a certain spatial development pathway in various geographic areas. We conclude about the effectiveness of the approach as a means of encouraging lay people and stakeholders to get involved efficiently in the management of ecosystems for securing the long-term provision of their services.

2 THE INVERSE APPROACH

Traditional mathematical modeling approaches use current data to predict and simulate future events. In the literature, this way of modeling systems is known as the *forward model* (Scales and Snider, 2000). Conversely, the inverse modeling approach (Aster et al., 2005; Scales and Snider, 2000; Tarantola, 2005) employs different mathematical techniques to derive from a given system state a set of model´s parameters which are commonly interpreted as the initial conditions of a evolving system. Recently, Grêt-Regamey and Crespo, 2011, and Crespo and Grêt-Regamey, 2011, proposed the use of an *inverse problem* approach for planning sustainable urban systems. In spatial planning, such *given future* corresponds to a desired future proposed by stakeholders. The resulting model´s parameters provide valuable information and help planners answer an important question for this approach: what do we need to do today in order to reach the desired future?

In a simply mathematical way, the inverse modeling can be expressed as a statistical formula of which components are the output of the system under study, a set of parameters describing the system (input of the system), and a mathematical operator relating the input and the output terms. The selection of mathematical operators depends on the type of phenomenon under study, thus it can take a wide variety of mathematical forms, such as ordinary differential equations (ODE), partial differential equations (PDE) (Ashter, 2005) as well as linear and non-linear functions.

Based on Aster et al. (2005), Tarantola (2005) and Pajonk (2009), the forward model can be generally formulated as follows:

$$d = G(\theta) + \varepsilon \qquad (1)$$

where d is a vector of outputs of the system, θ is a set of unknown parameters to be estimated, ε is a vector of unknown disturbances to be estimated. In turn G is a mathematical operator relating the outputs and the inputs of a system through the model's parameters. As oppose to the forward model, the goal of the inverse model is to search a solution for a given set of parameters, say θ^*, so that d becomes close to $G(\theta^*)$. In order to constrain the space of solution, we use a gray box modeling approach proposed by Pajonk (2009) and Jones et al. (2007) by which prior information on parameter values is employed to tackle the problem of multiple solutions. Such prior information may be provided as a more bounded solution interval for θ based on qualitative information from experts' opinion or as quantitative information from mathematical restriction of variables.

3 THE CASE STUDY: MANAGING ECOSYSTEM SERVICES TO FOSTER URBANIZATION

There seems to be a consensus among relevant investigators and planners that more research can be done to better understand the way ecosystem management and land use planning interact with one another. By means of a case study of land use change in Switzerland we first examine the main drivers of urbanization processes, and subsequently employ the inverse modeling approach to show through trade-offs between ES and related agriculture subsidies how suitable management of ecosystems can help planners achieve a desired level of urbanization in the future. We select two areas in Switzerland to perform our analysis: The Canton of Aargau, and the area of Thun. The Canton of Aargau is located in the north of Switzerland by the border with Germany. The Canton is divided in 11 districts and 231 municipalities with a population of 612,000 inhabitants and a population density of 436 inhabitants per square kilometer approximately. Aargau enjoys a prosperous economy activity with important sectors such as manufacturing, mining, construction, financial and insurances services, agriculture, forestry, timber, fisheries, restaurants and tourism. Broadly speaking, forest cover amounts at 42% of the entire Canton land cover, while agriculture and settlements amount at 48.3% and 9.7% respectively.

The region of Thun belongs to the Canton of Bern and is located toward the central west of Switzerland; its population approaches 42.000 inhabitants with a density of about 1.98 inhabitants per square kilometer. The economy of Thun is mostly based on tourism, agriculture as well as on engineering companies and machinery production. Thun enjoys a particular beautiful surrounding view overlooking the Lake of Thun and the Alps.

3.1 Data

The data selected for this study consists of land cover for the Canton Aargau and the region of Thun based on aerial photographs with 100x100 meter resolutions obtained through the Swiss Federal Statistic Office. Land cover was measured at two different time steps: 1994 and 1996/1997 for Aargau, 1993 and 1994/1996 for Thun. Land use covers were categorized into 5 types: extensive agriculture, intensive agriculture, forest, arable lands, and settlements. Figures 1 show the land cover for the study area.

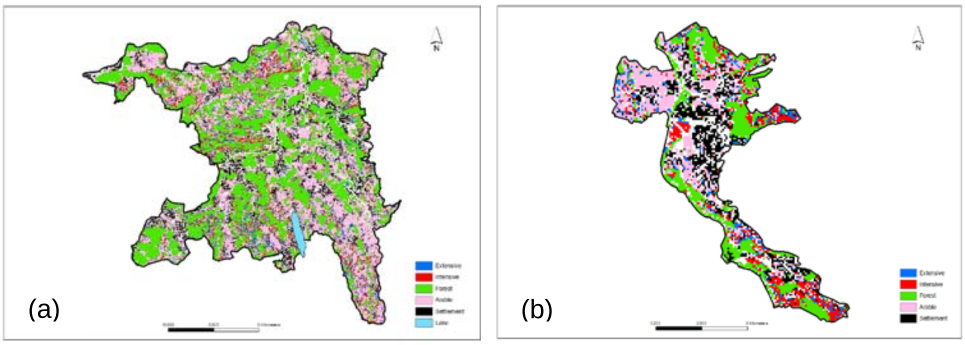

Figure 1. (a) Aargau land cover, 1994; (b) Thun land cover, 1994.

3.2 Methodology: A Logistic Regression Approach

As the forward model we choose a binary logistic regression to model agricultural – urban land use change in the Canton of Argau and the Canton of Thun. Equation 2 shows the mathematical formulation of the forward model in which for each cell *i* (100x100 m) of the study area the probability of agricultural-urban land use change is regressed on a set of explanatory variables:

$$\ln(p_i) = \beta_0 + \beta_1 x_{1,i} + ... + \beta_k x_{k,i} + \varepsilon_i \qquad (2)$$

The explanatory variables, represented by the set $\{x_1,.....x_k\}$, are categorized as *(i) geographical variables*: distance in meters to the nearest city or village (dist_sett), percent of the terrain slope (slope), and a dummy variable (dist_train) which is 1 if there is a train station in less than 1 km range, and 0 otherwise, number of cells in a rectangle of 300 x 300 meters of forest, extensive agriculture, intensive agriculture, and arable land use (neigh_forest, neigh_intensive, neigh_extensive, and neigh_arable respectively) *(ii) climate variables*: millimeters of precipitation per year (precipitation), daily average temperature in Celsius degrees (temp), and hours of sunshine per month (sun), *(iii) economic variables*: agricultural subsidies in Swiss francs per hectare per year (subsidies), and *(iv) ES*: agricultural production in Swiss francs per hectare per year (production), purification of ground water in Swiss francs per hectare per year (purification), the level of recreation measured in an ascending and categorical scale from 1 to 5 (recreation) and carbon sequestration in tons of CO_2 per hectare per year (co2). The model estimates the set of coefficients $\{\beta_0,....\beta_k\}$, and ε which is a stochastic term assumed to the randomly distributed. A final selection of the exploratory variables to substitute in Equation 2 was performed following a stepwise procedure based on the Akaike Information Criterion (AIC).

3.3 Results

The outcomes of logistic regressions for Aargau and Thun are reported in Table 1 and 2 respectively. Two points are worth mentioning: (a) parameters estimates for distance to settlement and slope variables are statistically significant for Aargau, but not so for Thun. Such parameters estimates are usually important drivers for land use changes and therefore are generally statistically significant in land use models. In the case of the region of Thun, the negligible statistical significance for the dist_sett parameter may be explained by the clustered spatial pattern of settlement areas. As can be seen in Figure 1(b), a clustered band of settlement runs along the region of Thun, thereby low variability in the distance between cells and the nearest village is expected. Additionally, the region of Thun is characterized by an even and flat terrain surface surrounded by steep mountains which explains the low statistical significance of the slope parameter estimate, (b) important differences in both signs and statistical significance are observed for parameters estimates associated to ES variables between Aargau and Thun. Such differences suggest that land use planning is not aware of the value of ES so that ES are not included in land use planning (at least in urbanization processes). For example, the case of groundwater purification whose parameter estimates takes on a positive value for Aargau and a negative value for Thun. Though it may not be absolutely clear a priori whether or not higher levels of groundwater purification favor urbanization, dissimilar signs found for the associated parameter estimates in both areas reveal a low understanding of the interaction between groundwater purification and urbanization processes. Similarly, the negligible statistical significance of agriculture production and CO_2 sequestration parameter estimates for Thun indicates that neither of the values of the associated ecosystem services is under consideration in the land use decisions.

Table 1. Logit parameter estimates for Aargau

Variable	Parameter estimate	z-value	
intercept	-2.75400	-1.38	
dist_sett	-0.00030	-10.60	****
temp	0.22120	2.34	**
precip	-0.00448	-6.10	****
sun	0.01491	0.50	
dist_train	0.66790	9.84	****
neigh_forest	-0.47280	-14.28	****
neigh_intensive	-0.77500	-17.79	****
neigh_extensive	-0.55790	-14.57	****
slope	-0.02332	-4.81	****
subsidies	-0.00058	-2.68	**
production	0.00009	3.00	***
purification	0.00022	6.55	****
recreation	-0.23420	-3.20	***
co2	0.01080	2.90	***

AIC=9979.4
** significant at 0.05% level
*** significant at 0.001% level
**** significant at 0.00% level

Table 2. Logit parameter estimates for Thun

Variable	Parameter estimate	z-value	
intercept	11.83157	1.74	*
dist_sett	-0.00010	-0.55	
temp	-0.90510	-2.40	**
precip	-0.00351	-1.68	*
slope	0.00529	0.24	
dist_train	1.08604	3.387	****
neigh_forest	-0.63496	-4.30	****
neigh_intensive	-0.78033	-5.82	****
neigh_extensive	-0.79531	-4.02	****
neigh_arable	-0.60626	-7.65	****
subsidies	-0.00121	-0.931	
production	0.00011	0.51	
purification	-0.00050	-2.91	***
recreation	0.34567	3.74	****
co2	-0.00126	-0.08	

AIC=540.1
** significant at 0.05% level
*** significant at 0.001% level
**** significant at 0.00% level

3.4 Trade-off analysis between ecosystem services: the inverse model approach

To solve Equation 2 we select from the study area two small clusters of agricultural lands. Both clusters lay on catchment areas, and their locations, one in Aargau and the other in Thun, are shown in Figure 2.

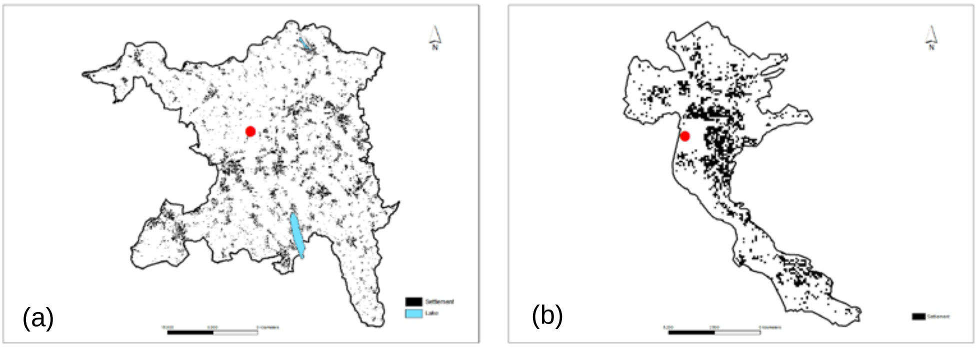

Figure 2. (a) Location of cluster in Aargau. (b) Location of cluster in Thun

Solving the logistic model provides the probability of agricultural - urban land use change based on both the data and the location-specific values for the explanatory variables. For example, point 1 displayed in Figure 3(a) illustrates for the Aargau's cluster the land use change probability for one explanatory variable, more precisely, the subsidies variable. When the probability for this cluster approaches zero, the level of agricultural subsidies is about 1040 [CHF/ha.year] observed in 1994 (point 1). Following the traditional forward approach, future probabilities can be forecasted by providing different level of agricultural subsidies. In contrast, the inverse approach provides the level of agricultural subsidies for a desired level of urbanization, that is to say, for a given level of land use change probability. For example, let's suppose that we want to increase the current level of probability for the Aargau's cluster from the approximately current level of 0 to 0.05 in the future. In such case, we can use iterative approximation methods to solve Equation 2 for the subsidies variable, which in this example correspond to the θ^* term of Equation 1, while the 0.05 probability correspond to the d term of the same equation. This leads to point 2 of Figure 3(a) which provides the level of agricultural subsidies to achieve the desired level of urbanization. Example displayed in Figure 3(a) is the simplest solution of the inverse approach as the model is solved for only one variable. However, the problem can be solved simultaneously for more than one variable. In this way, trade-offs between variables can be used to achieve the same desired level of urbanization. This is illustrated in Figure 3(b) in which the straight line represents the combination of different solutions for groundwater purification and subsidies in order to achieve the same level of urbanization of point 2 in Figure 3(a), that is, a land use change probability of 0.05.

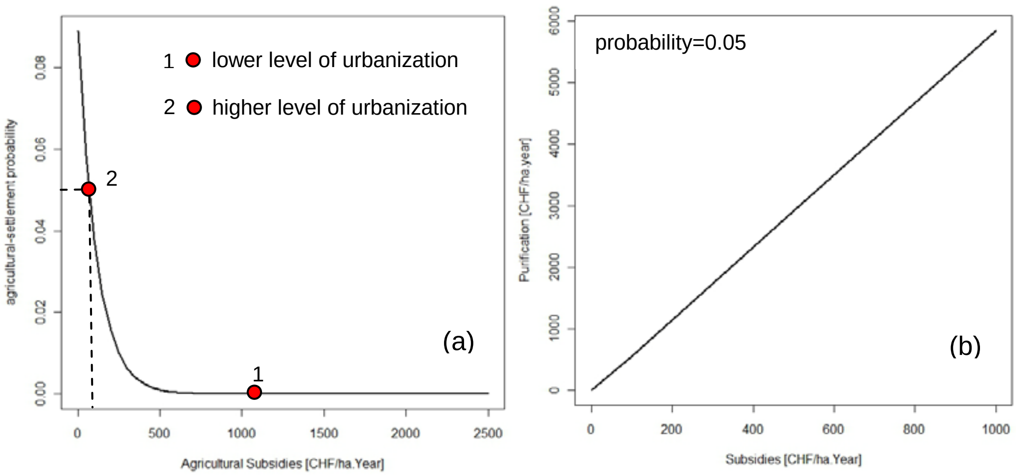

Figure 3. (a) Probability of urbanization v/s agricultural Subsidies. Moving from point 1 to point 2; (b) Trade-off between purification and subsidies to reach point 2.

Next, a similar analysis is done for the cluster in Thun. Since in the region of Thun the agricultural subsidies have not influence on the conversion of agricultural lands to urban areas (see Table 2), we perform the analysis using two ES: recreation and purification. Firstly, as with the example for Aargau, we solve the inverse problems for one variable, in this case the recreation ecosystem service. Coordinates of point 1 in Figure 4(a) are (1,0.07) which correspond respectively to the probability of agricultural-urban land use change and the observed level of recreation level in 1993. To illustrate the strong effect of the level of recreation on the urbanization process in Thun, we choose 0.5 as the desired future probability of agricultural-urban land use change. As can be seen in Figure 4(a), the abscissa of point 2 (around 1.7) is the level of recreation to achieve in the future a probability of agricultural-urban land use change of 0.5. Thus, a rather small change in the recreation level brings up the probability from a close to zero level to a high level of 50% probability from agriculture to settlement. This result is clearly indicating that areas which are good for recreation are also suitable for settlements. In this sense, and from a planning perspective, the model provides useful information on possible areas for densification, however it must be said a densification process in such areas also means a loss of high quality recreational areas.

Figure 4(b) displays the trade-off between groundwater purification and the level of recreation to achieve the same 0.5 probability. In contrast to Aargau, the higher the level of groundwater purification, the lower the probability of agriculture-urban land use change. Therefore, according to the current manner of managing and valuating the ES across the region of Thun, higher levels of groundwater purification must be necessarily compensated with higher levels of recreation in order to increase urbanization.

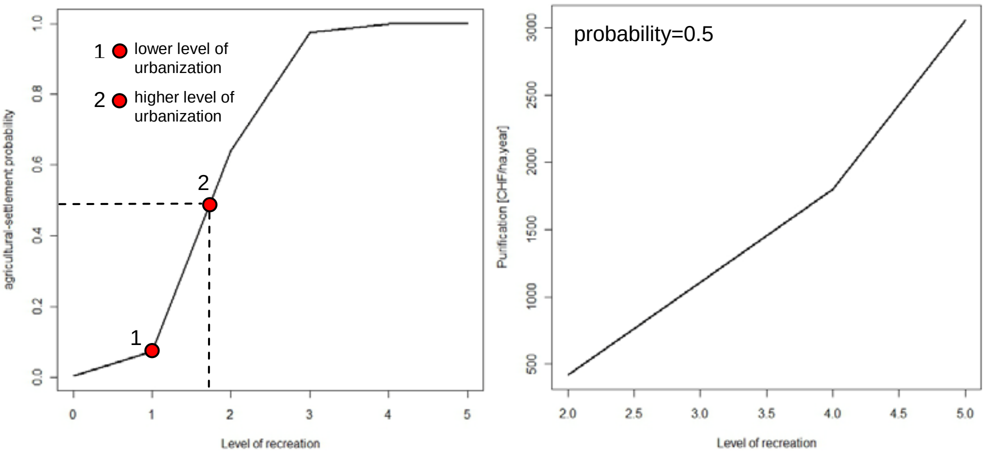

Figure 4. (a) Probability of urbanization v/s level of Recreation. Moving from point 1 to point 2; (b) Trade-off between purification and level of recreation to reach point 2.

4 CONCLUSIONS AND RECOMMENDATIONS

In this work we illustrate how the inverse modeling approach can be used to support land use planning. We focus our analysis preferably on ES and how trade-offs between ES broaden the number of different transition pathways to achieve future planning decisions in a sustainable manner. Results of the study also reveal that some ES are not included in planning decisions (for example, carbon sequestration). Urbanization or any other land use change process should however not be done without taking into considering ES values, as they contribute to human welfare, both directly and indirectly. By using an inverse approach method, this study quantifies the required ES necessary to achieve a future planning goal (level of urbanization to be more specific) - a novel and technically useful information to planners aware of the importance of the long-term provision of ES for sustainable spatial development. As a way to simplify the illustration of how the inverse approach operates, we use in this study a global model without addressing the spatial correlation or the error term. Therefore, for future research we suggest the use of more complex formulations accounting for the spatial structures of the data. One option is the use of spatial autoregressive models proposed by Anselin, 1988, and Pace et al., 1998. Alternatively, the spatial autocorrelation of the error term can be caused purely by model misspecification as suggested by McMillen (2003), thereby the problem might be addressed by the inclusion of additional explanatory variables into the land use model.

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