Pimp your landscape – a cellular automaton approach to estimate the effects of land use pattern changes on environmental services

Fürst, C. (1); Lorz, C. (1); Pietzsch, K. (2); Koschke, L. (1); Frank, S. (1); Makeschin, F. (1)

(1) Institute for Soil Science and Site Ecology, Dresden University of Technology, Pienner Straße 19, 01737 Tharandt, Germany,
fuerst@forst.tu-dresden.de

(2) PiSolution GmbH, Hauptstraße 12, 04416 Markkleeberg, Germany

Abstract: Pimp your landscape is a software tool, which was developed to facilitate the evaluation of different land use management scenarios regarding the impact of land use pattern changes on environmental services. The article introduces the technological and scientific approach of the software, which can be characterized as modified 2-D cellular automaton with GIS features. The cells have the major attribute “land use type” and can be attributed with additional environmental information such as geological, topographic and climate data. The GIS features support to delineate non-cellular infrastructural elements such as roads, rivers, water bodies or power plants. A central element in the system configuration is the evaluation matrix, where values are assigned to the land use types and infrastructural elements on a relative scale from 0 (lowest value) - 100 (highest value) regarding their contribution to environmental services. Also of central importance is the possibility to configurate rules, which describe the impact of environmental attributes and proximity effects on the cell values and on the transition probability of the land use types. The user interface and usage of the software including an exemplary application case are demonstrated. Finally, constraints and limits in the actual use with focus on the implications of the evaluation method and the modified cellular automaton approach are discussed and an outlook on the further development is given.

Keywords: land use management planning; environmental planning; management planning support; initial estimate of planning measures; cellular automaton based software

Introduction

Land use management planning is confronted with the challenge to consider at the same time conflicting demands of various land users, various interactions between different land use types and a complex bundle of socio-economic and environmental impact factors with different impact intensity on different land use types (Parker et al., 2008). A related challenge is the necessity to think, plan and act on different scale levels (Rossing et al., 2007). For spatial planning, the meso-scale level is the most important scale, where e.g. decisions are made on the optimization of the land use pattern in water catchment areas to avoid flood events and to ensure drinking water supply (Steinhard and Volk, 2003; Volk et al., 2008). “Pimp your landscape” was originally developed to support participative and group communication processes on meso-scale level (Fürst et al., 2008; Fürst et al., 2009). The name “Pimp your landscape” originates from this initial application field and expresses the intention to give the user the freedom to design the landscape according to his ideas with an approved feed-back on the effects for important goods and services.

The objectives of Pimp your landscape are (a) to support planners in a fast simulation of alternative land use scenarios and a fast assessment of their possible advantages or disadvantages for regionally important environmental services. (b) The system should support an easy integration of environmental impact factors, such as climate data, pedological / geological and topographical data into the impact assessment. (c) The system should support to integrate the interactions between different land use types and their implication for the impact of planning measures on environmental services. Planning measures can be realized in the software by modifying the mosaic of land use types or by establishing linear infrastructural elements such as roads or highways, irregular spatial elements such as water bodies and point shaped elements with spatial impact gradients such as power plants. The environmental services, which are integrated into the impact assessment, are specified by the user, which in this case is the regional planner or sectoral experts involved in regional planning processes.

The article introduces (a) the technological and scientific approach of Pimp your landscape and (b) describes the user interface and usage of the software including an exemplary application case. (d) Constraints and limits in the actual use are discussed and an outlook on the further development is given.

1. Material and Methods

1.1. Technological and scientific approach

To correspond to the objectives described in chapter 1, a technological approach was chosen, which is based upon a 2-D cellular automaton (Fürst et al., acc.). In accordance with the cellular automaton approach, the smallest unit within the system is a cell, which represents an area of 100 x 100 m² and which interacts rule-based with its neighboring cells. A cell can only be attributed with one land use type. Land use types with a small

share within a cell are assigned automatically to the dominating land use type. With regard to proximity effects, a Moore neighborhood (nine-cell neighborhood with range r = 1) is used. Rules for enabling or restrict the transition of one land use type into another and for evaluating the effects of updating the land use types are defined by the user and consider the cell state, the states of neighboring cells, cell attributes such as environmental data, the presence or absence of linear (e.g., streets, rivers) or point-shaped elements (e.g., power plants) and thresholds for the maximum or minimum share of a land use type.

The demand to integrate variable environmental parameters in addition to the land use type as basic attribute of a cell made it necessary to modify the original concept of a cellular automaton. The software was complemented by features of a Geographical Information System (GIS), which enable to import and overlap different information layers and to assign different attributes to the cells as described e.g. by White and Engelen (1997) and Couclelis (1997). Additionally, features were introduced, which enable to "draw" non-cellular infrastructural elements into the maps. These can be linear elements such as roads or rivers, irregular spatial elements such as water bodies and point shaped elements with a spatial impact gradient such as (chemical) industrial factories or power plants. In this latter case - as an exception - the Moore neighborhood is modified for a consideration of proximity effects, whose spatial extent can be defined by the user. The irregular spatial elements are handled in the same manner as the land use types, the linear and point shaped elements are handled as cell attributes. The linear elements can be classified into different categories according to their size and in case of roads according to their status (local, regional, national) and use intensity. This differentiation into categories is considered in the evaluation results and serves also for the formulation of the rules.

A major contrast to cellular automata is that Pimp your landscape does not automatically update all cell states on the basis of local rules, which specify the transition probabilities. In our case, the user has to configure rules, which determine if a land use type is allowed to be converted (transition probability = 1) or not (transition probability = 0) into another land use type. He must decide by mouse click and guided by the before configured rules, at which point of time he wants to change a cell, a part of the region or insert a linear, irregular or point shaped infrastructural element. This user-driven and non-automatic updating corresponds to demand (c) and was chosen to increase the transparency of the outcomes of the evaluation. The user can then directly experience the effects of each change he is carrying out. A term to reflect the way in which Pimp your landscape is working would probably be "2-D cellular semiautomaton with GIS features".

1.2. Data base

The basic data set of Pimp your landscape are "Corine Landcover (CLC) 2000" maps or comparable land cover maps on national level (biotope type / land use type maps). Additional cell attributes, such as geo-pedological, climatic or topographic information can be imported as geo-referenced information layer. They are overlapped in the system with the land cover maps and their information can then be assigned to the cells. In case that

information on the land use type or other cell attributes is missing or not available in parts of a test area, it is also possible to complement existing maps or to create a requested information layer by a "map design" feature. In opposite direction, data sets after simulation can be exported as geo-referenced text or shape file for further use in a GIS.

1.3. Evaluation approach

The evaluation of the impact of planning measures follows a hierarchical approach (Fig. 1) and is carried out as moderated process. The evaluation starts (a) by selecting the land use types and by defining additionally types and size categories of linear, irregular or point shaped infrastructural elements, which are of regional relevance. (b) The user has to specify the environmental services of regional interest. The land use classification standards of CLC 2000 and the environmental services (and functions) (LUF) set described by Perez-Soba et al. (2008) are available as initial settings. The user can modify these initial settings or adopt completely different settings according to the regional application targets.

In a subsequent step, the resulting value matrix must be filled out. Indicator sets are selected on the basis of literature analysis and expert knowledge, which provide regionally suitable information on the impact of the land use types and infrastructural elements on environmental services. The final identification of appropriate indicator sets is realized in several feed-back loops with regional experts. Based on this aggregated information, the impact of each land use type and each type and size categories of infrastructural elements on each environmental service or function is ranked on a relative scale from 0 (lowest value) to 100 (highest value). The introduction of this relative scale aims to facilitate the multi-criteria evaluation of planning measures. The value matrix contains initial impact values of the land use types and infrastructural elements on the environmental services. Note that in the evaluation philosophy of Pimp your landscape, the initial value of a land use type for a environmental service represents the maximum in the regional context, which can only be reduced (a) with regard to environmental cell attributes from additional information layers such as height above sea level, mean annual precipitation and temperature, soil type and exposition. (b). The impact of the cell environment (homogeneous land use types vs. different land use types) and neighborhood type (edge to edge vs. corner to corner) can impact the original maximum value. The consideration of these two impact factors (a) and (b) in the total evaluation is supported by rule setting options (see chapter 2.4).

Linear and point shaped elements are handled as additional cell attributes. Their values for the environmental services in the matrix serve to calculate for the cell to which the respective attribute is assigned a corrected value for the environmental services, which results according to the actual status of the system to 50 % from the land use type and to 50 % from the value of the linear or point shaped element.

The evaluation result so far is based on the assumption that each land use type and

infrastructural element as soon as it is established has its full value for the environmental services (time point tn). To come to a more realistic evaluation with regard to ecosystem dynamics, the possibility to define time dependent differences in the land use type values for time slots is introduced. These time slots can be individually specified by the user e.g. in matters of regular time slots of 10 years until tn, or related to the needs in sectoral planning in the form of irregular time windows of 10, 30, 50 and 100 years. The time dependent modification can be done for all environmental services or only for selected ones.

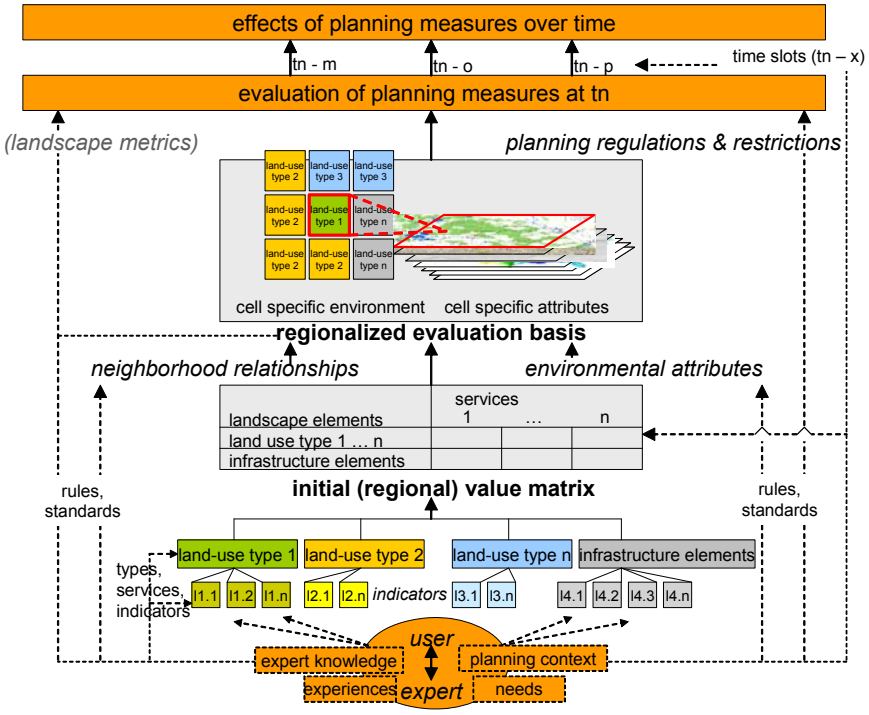

Figure 1. Hierarchical evaluation in Pimp your landscape.

For upscaling the evaluation to the regional level, a weighted mean is calculated for each environmental service by summing up the values of each cell for the singular

environmental services and dividing the sums by the total number of cells. To exclude any influence on the evaluation result by impact factors such as cell size, the latter is fixed to 100 x 100 m².

1.4. Rule setting

In addition to the possibility to design a regionally adapted value matrix, Pimp your landscape enables to specify regionally applicable planning rules and restrictions. These rules affect either the evaluation results (see chapter 2.3) or decide upon the transition probability of a land use type in dependence from proximity effects and cell attributes. The following rule setting options are available in the actual software version:

(a) Rules affecting the evaluation results

(a1) The impact of environmental attributes of the cells on the initial value of a land use type for an environmental service can be expressed by a percentage reduction of the initial value. As an example, the initial value of a deciduous forest for the service "land based production" (according to Perez-Soba et al., 2008) can be decreased in dependence from the height above sea level with respect to the impact of the length of the growing season on the biomass production.

(a2) The impact of proximity effects can be expressed as percentage reduction of the initial value of a land use type. Proximity effects are assumed to occur only in the case that two different land use types are neighbors. Following the model of a Moore neighborhood, different neighborhood types are considered. A longitudinal neighborhood has the full impact, whereas the impact is reduced as a commitment to 25 % in the case of the diagonal proximity of the cells. As an example for this rule, the value that is assumed for an agricultural site for the service "land based production" can be decreased by its proximity to a forest due to its shadowing effects.

(a3) In the case of point shaped elements, the user must specify the spatial distance up to which its impact is valid and up to which a percentage reduction of the original cell values should be considered. It must also be specified, which environmental services are impacted. The spatial distance and the number of neighbors that are affected in each direction are simply defined by freehand delineation on the map. The gradient can be centric or irregular, even with an excentric localization of the point-shaped element. Within the gradient, a linear decrease of the impact is assumed starting with the highest impact (full percentage reduction) on the original values of the land use types at the cells nearest to the point shaped element.

(a4) The user can set minimum or maximum thresholds for the environmental services on a scale from 0 - 100. This offers the option to reflect political targets in planning, such as keeping biodiversity or water quality at a certain level. In the case, a maximum threshold is

surpassed or a minimum threshold is undergone, a warning message is given. The user has to go back in the simulation and to re-establish a status with no violation of a threshold before continuing.

(a5) Time dependency of the land use type values for environmental services can be specified as described in chapter 2.3. The user can decide for which land use types such trends apply and must define first, which time slots should be considered in evaluation, and next insert the time-dependent value of the land use type for environmental services, for which temporal trends are relevant

(b) Rules affecting the transition probability of land use types

(b1) The user can specify, which land use type is basically allowed to be converted into another. Following the philosophy described in chapter 2.1, there are only two options: the conversion is allowed (transition probability = 1) or forbidden (transition probability = 0). Different from the pure cellular automaton approach, the probability that a user changes a land use type into another is managed by the value matrix described in chapter 2.3: each conversion from one land use type into another impacts the value of the cell for different environmental services and in consequence the result, which is achieved for the total landscape. A conversion of a land use type with high value for an environmental service into another with a low value is in consequence “punished” and therefore less probable.

(b2) The possibility to convert a land use type into another can be restricted in dependence from environmental cell attributes and in dependence from the presence of a linear or point shaped element. Again, a conversion is only allowed or forbidden. To overcome the problem of an “undesirable” or “unrealistic” conversion, the impact of the environmental attributes on the evaluation result was introduced as described under (a1).

(b3) The possibility to convert a land use type into another can be restricted by its neighboring land use types. In this case, all nine neighboring cells are regarded and equally weighted. Also here, only two transition probabilities are integrated as undesirable changes are again “punished” by the rule described under (a2).

(b4) Global thresholds for the minimum and maximum share of a land use type and trends for its development (increase, decrease, remaining equal) can be specified and can stop the conversion into a land use type.

All rule setting options can be used singularly. The rules described under (b) can also be combined and saved as a rule set for translating complex planning restrictions as they might be given in the frame of laws or EU directives.

2. Results

2.1. Rule setting

Pimp your landscape is conceived as online tool. The user starts with uploading the requested data sets. This is supported by an external routine, where the user can delineate the desired test region on the basis of an adapted OpenStreetMap routine. After delineating the test region, the requested data sets are automatically bundled together with infrastructural information from OpenStreetMap into a .zip-file, which then is uploaded in Pimp your landscape. As soon as the (geo-referenced) maps are uploaded, they are automatically overlapped.

In a next step, the evaluation matrix must be configured and filled-out. Up to ten environmental services and an unlimited number of land use types or infrastructural element types can be defined whether on the basis of the CLC 2000 standard or independent from it. Fig. 2 shows an example of such a matrix. The initial matrix forms the basis for time slot specific matrices, where the values of the land use types can be modified if their impact on environmental services is time dependent. As an example, the provision of biomass and fulfillment of ecosystem services of forest land use types is strongly dependent from the stand age and development stage. The time slot specific matrices have to be saved with a name indicating the time slot for which they are valid and are then available in combination with their initial matrix.

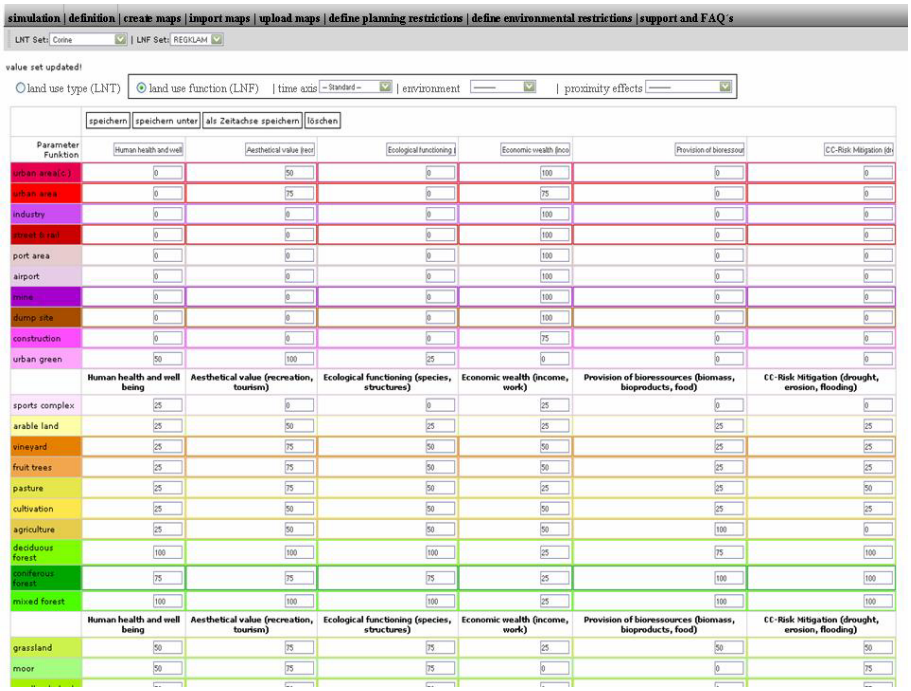

Figure 2. Exemplary evaluation matrix.

In the following, the user can specify the rules and thresholds described in chapter 2.4. Fig. 3 shows as an example for the evaluation relevant rules the routine for fine tuning the impact of environmental attributes on the cell values (rule a1). Fig. 4 shows as an example for the transition probability relevant rules a screenshot of the matrix, where basic specifications are managed if the conversion of a land use type into another is allowed or not (rule (b1)).

Figure 3. Screenshot of the routine how to reduce the value of a land use type in dependence from environmental factors.

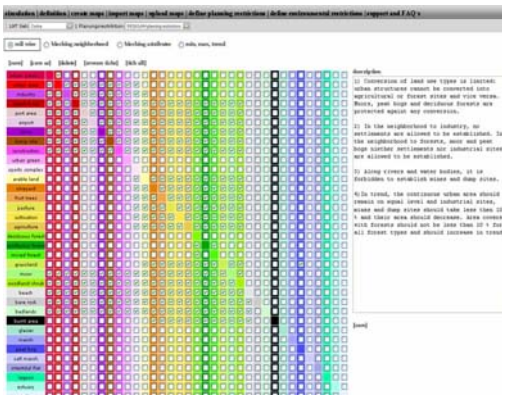

Figure 4. Screenshot of the routine how to set the transition probability of a land use type.

After having finished these initial steps, the simulation run can be started for the selected region. The legend can optionally be activated by mouse click and informs the user about the colors of the land use types and their regional value on a relative scale from 0 - 100. Fig. 5 shows the user interface without activated legend.

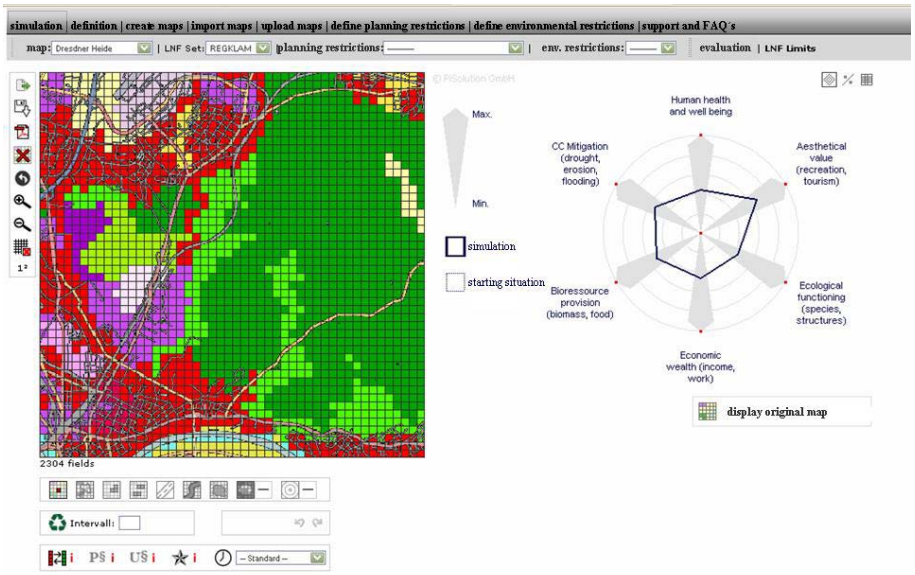

Figure 5. User interface of Pimp your landscape.

The buttons on the left side of the map enable standard functions such as saving the simulation run, converting the results into a pdf-file, zoom functionality or modification of the displayed raster size in the map. The buttons below the map are relevant for the simulation itself. The buttons in the first line below the map offer different instruments to change the land cover and to insert additional infrastructural elements. From left to right, the buttons enable to convert the land use types cell wise, to delineate freehand an area to be converted, to convert all neighboring cells with the same land use type or to convert all cells with the same land use type in the total map. The subsequent buttons support to draw freehand roads, rivers and water bodies with different size categories. The last two buttons are dedicated to special system functionalities. The button next to last allows to zoom into a part of the map and to compare the evaluation results for the zoom area with the results for the total map. It is possible to define several zoom areas in parallel. The selection box right to the button allows to switch between the zoom areas and to compare in the diagram right to the map their results in relation to the results on landscape level. This feature supports the pre-estimation of possible localization alternatives for highly sensible planning measures such as the construction of a highway junction or the establishment of a dumpsite (see chapter 3.2 application example). The last button is dedicated to insert point shaped elements and to delineate freehand their impact gradient. Fig. 6 shows an exemplary screenshot, where a matrix pops up, which enables to specify the impact of the gradient on the different environmental services.

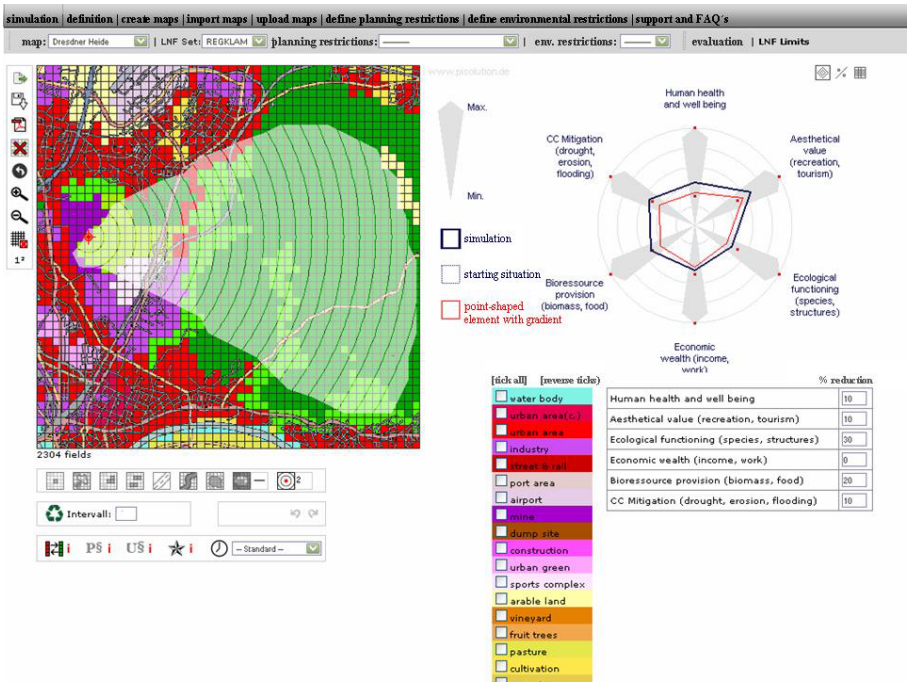

Figure 6. Establishing a point-shaped element and defining the impact gradient regarding different land use types and environmental services.

Also in this case it is possible to introduce several point shaped elements with gradient in parallel and the selection box right to the button enables to switch between them and to compare in the diagram right to the map their impact in relation to the reference situation without them. This feature is thought to support the pre-estimation of possible localization alternatives for infrastructural elements such as power plants or industrial emission sources.

The buttons in the line below enable to define - if desired - intervals, where the evaluation results in the diagram right to the map are automatically actualized, the green arrow starts a replay of all changes made so far, which can be interrupted to restart the simulation at any point where the user wants to modify the changes so far. The other two arrows enable to repeat or reverse a simulation step.

The information buttons in the third line below the map give written information on the rules, the user has specified in case he wants to understand better a simulation result, a warning message or why a conversion he wants to carry out is not possible. The watch enables to switch between different time slots. To activate this feature, the simulation must be finished and differences in the evaluation for different time slots are displayed in the diagram on the right side of the map.

The diagram on the right side of the map gives permanently information on the results of the simulation compared to the starting situation as reference. It is also possible to switch to a land use type statistic, which indicates the percentage changes in the share of all land use types. Finally, the user can also switch to a trend table, which gives information on the start values of the environmental services, the actual values and visualizes the development trends by arrows.

To support the visual comparison of the original landscape and the simulation result, the original situation can be displayed in parallel to the map by clicking the icon “display original map” on the right-hand side. The figure that is then displayed cannot be changed by the user, and its position can be moved with the mouse to avoid obscuring the diagram, trend table or land use type statistic.

2.2. Application example

Pimp your landscape is actually configured to be used in the project REGKLAM (www.regklam.de) for the comparison of different land use scenarios with regard to their impact on environmental services and their ability to mitigate undesirable development trends under climate change in the metropolitan area of Dresden, the capital of the federal state Saxony, Germany. Therefore, six regionally important environmental services were selected together with the regional planners: (1) human health and well being (water and air quality), (2) economic wealth (income and provision of working places), (3) aesthetical

value (intensity of recreation and tourism activities), (4) ecological functioning (richness in species and structures), (5) bioresource provision (provision of biomass and food) and (6) climate change mitigation (ability to mitigate the risk of drought, erosion and flooding).

The integration of different climate change scenarios is not yet finished, but first tests of regional development strategies and local planning measures are yet done. The following Figs. 7 - 13 show as an example the test of a local planning measure in the "Tharandter Wald", a part of the metropolitan area of Dresden with regionally high importance for recreation. Fig. 7 shows the initial situation of the Tharandter Wald area including the city of Tharandt and some smaller settlements. According to the actual status of discussion in the evaluation of environmental services within the REGKLAM project, the fulfillment of the regionally relevant environmental services exceeds the regional minimum thresholds, which are indicated by the inner red dots in the diagram, with an exception in the environmental service "economic wealth". Therefore, planning measures are tested, which help to overcome at least partially this shortcoming, such as the allocation of land for industrial sites. The question to answer in this application case was to identify an optimal localization for a new industrial site of 100 ha combined with additional 10 ha of dump sites and an upgrading of a local road to a highway as accompanying development measure.

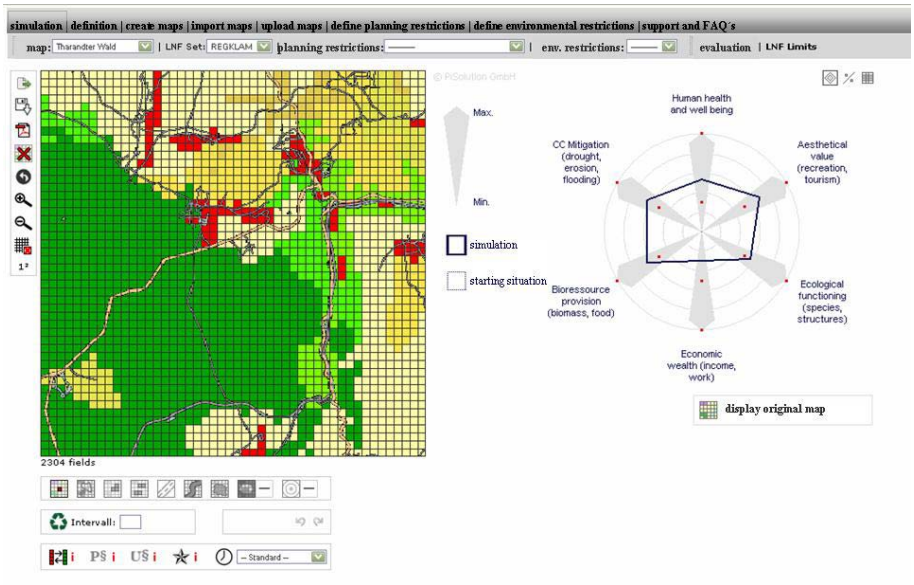

Figure 7. Initial situation of the test area Tharandter Wald.

For establishing the industrial site, two basic alternatives are possible: (a) the industrial site could be situated as far as possible from the settlements in the forest (area focus in Fig. 8). This alternative is preferred by the communal planners. It has a low conflict potential regarding the landownership because the forest is state owned. However its conflict potential regarding the recreation interest of citizens is expected to be higher. (b) The industrial site could else be situated the Northeastern part of the area nearer to the settlements, but on sites, which are less relevant for recreation (area focus in Fig. 9). In this case, a higher conflict potential is expected regarding a more heterogeneous landownership and a lower conflict potential is given with regard to regional recreation demands. In both cases, a close spatial connection to one of the larger roads, which can be upgraded, is demanded.

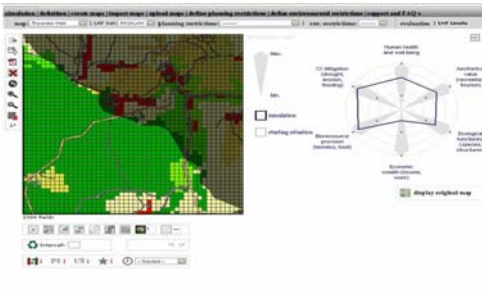

Figure 8. Planning alternative (a)- focus on the forested part of the test area.

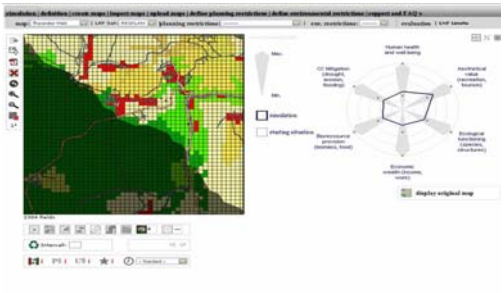

Figure 9. Planning alternative (b) - focus on the agricultural part of the test area.

Figure 10 shows the effects of alternative (a) for the total area, the industrial site is violet colored, the dumpsite is brown colored. Fig. 11 zooms into the forested part. Fig. 12 shows the effects of alternative (b), Fig. 13 zooms into the Northeastern part of the area. In the regional planning process, it could now be demonstrated that the effects of alternative (b) with reference to the starting situation are less grave for all affected environmental services either for the total area of Tharandter Wald (Fig. 12) and also for the Northeastern focus area (Fig. 13) compared to the effects of alternative (a).

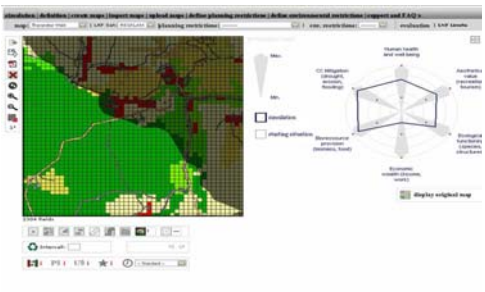

Figure 10. Global effects of the planning alternative (a) for the whole test area.

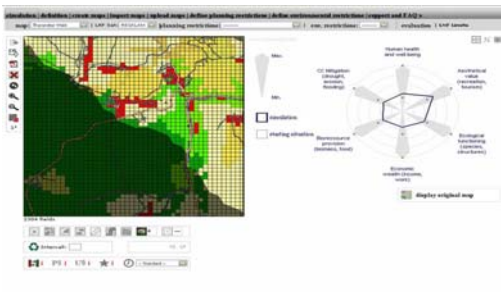

Figure 11. Local effects of the planning alternative (b) with focus on the forested part of the test area.

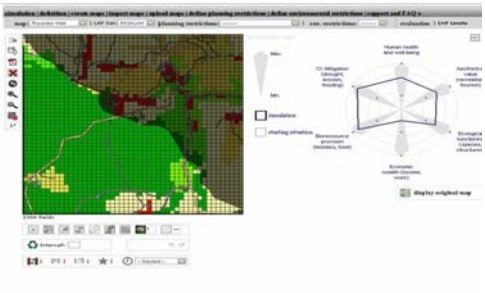

Figure 12. Global effects of the planning alternative (b) for the whole test area.

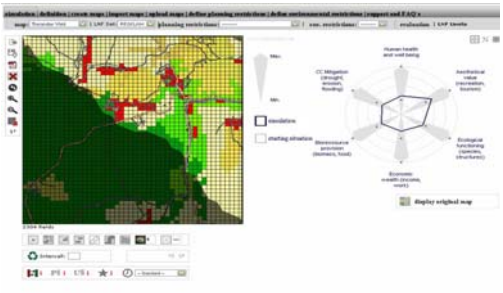

Figure 13. Local effects of the planning alternative (b) with focus on the forested part of the test area.

Of course, also variable other alternatives are tested including measures to compensate the losses in environmental service fulfillment. The displayed simulations are only thought as an example for the functioning of the system.

Discussion and conclusions

The presented approach of Pimp your landscape assumes that the target group planners is mainly interested in a pre-estimation of planning effects, which implies that qualitative information on the improvement or worsening of environmental services is sufficient. This aspect was discussed and tested in the development phase of the software with many representatives from the planning practice and is still in discussion and under development in the REGKLAM project. To reference the land use type impact on environmental services on a relative scale from 0 - 100 represents a highly aggregated evaluation result. This approach was chosen, because the support of land use management decision faces one major problem: cross-sectoral indicators or indicator sets for comparing the impact of different land use types on a selected environmental service are mostly not available. Either the sectoral evaluation methods are different or often the reference scale levels are different (Yli-Viikari et al., 2007; Wijewardana 2008). This makes it impossible to display directly key indicators or indicator sets as evaluation result.

A related constraint in the acceptance and use of Pimp your landscape is the missing interface to or coupling with models. Basing Pimp your landscape on models would provoke the same problem as described for the indicators: the use of models from different land use sectors is often hindered by their different reference scales and the related problem to up- or downscale modeling results to ensure the requested linkages between the models (e.g. Rossing et al., 2007). Taking landscape hydrology and forestry as an example, models are often overparameterized, which confines their use to the regions, where they originally

where developed. Systems based on (coupled) models are difficult to administer and to transfer from one region to another (Malczewski, 2004). Furthermore, there are few models covering the interactions between land use types in a landscape context (see e.g. Lambin et al., 2000; Roetter et al., 2005; Verburg et al., 2006).

Therefore, the approach of basing the software on the principle of a cellular automaton was chosen. It was considered as most appropriate solution (a) to integrate in a generalizeable way spatial interactions between different land use types, which impact the transition probability of a land use type (White and Engelen 1997; White et al., 1997) and (b) to standardize the description of further interactions between the land use types by the possibility to reduce the value of a land use type in dependence from its neighbors.

The cellular automaton based approach as realized in Pimp your landscape implies however still a shortcoming with regard to a holistic evaluation of the land use type mosaic: environmental services related to ecological aspects and ecosystem functioning as well as to aesthetical characteristics of a landscape or the use of high tech cultivation methods, cannot be evaluated on the basis of counting cells. They must consider aspects such as size and form of areas with a specific land use type, the border length between neighboring land use types and the spatial connectivity of areas with the same land use type in a landscape (Uuemaa et al., 2009; Uuemaa et al., 2005; Botequilha Leitao and Ahern, 2002). In consequence the possibility to complement the evaluation by the use of landscape structure indices (landscape metrics) is actually tested, including a validation of the systematic error in the evaluation, which is provoked in Pimp your landscape by rasterizing the original landscape structures.

Pimp your landscape is designed to support a fast and easy analysis of the impact of planning measures on environmental services. The tests so far in different projects and application cases, of which an example from the REGKLAM project was selected, have shown that this demand is fulfilled. From planning practice however, the request came up to support an automatized estimation of “best alternatives” for planning measures. Apart from the technical complexity, this would probably reduce the comprehensibility of the outcomes (“black box style”, Malczewski 2004) and is therefore considered as a system limit, which will not be passed over in near future.

The actual working areas for an improvement of the software and its outcomes are focused therefore on the integration of landscape metrics and the development of a standardized evaluation approach. Furthermore, Climate Change related risks (erosion, drought and flooding) are planned to be included in the evaluation by completing the data sets (risk maps) and enlarging of the possibility to use and value linear landscape elements (hedges, fences, ditches).

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