A Web-Based Dashboard for Estimating the Economic and Ecological Impacts of Land Use Class Changes for Key Land Patches

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Abstract. The increasing pressure on land coming from the raising needs of a fast-growing population puts public and private landowners and decision makers in front of difficult choices concerning the best use of limited land resources. On one hand, agricultural land and grassland need to be used to support human food requirements. On the other hand, these land uses create trade-offs with other ecosystem functions, assets and services, such as ecological connectivity, biodiversity and natural habitat maintenance. In this paper a prototype web-based dashboard is presented, that aims at allowing a fully-fledged calculation of the economic and environmental trade-offs between different land uses of any land patch (excluding urban areas and infrastructures) and in the Grand Duchy of Luxembourg. An agent-based model (ABM) coupled with life-cycle assessment (LCA) runs on the background of the dashboard. The coupled model allows the simulation of the farm business and the calculation of the revenues made by farmers in every land patch under different farm management scenarios. Crossing the information coming from the model with other tools would also allow to integrate local environmental trade-offs, such as degradation of local habitats or ecological connectivity, and not only global ones defined in a non-spatialized way. The dashboard has a potentially high value to inform policy, strategies, or specific actions (e.g., environmental stewardship programs that integrate economic convenience as a condition) and has the necessary flexibility to integrate new aspects related to territorial analyses as they become available.

Keywords: Visualization tools · Farmland · Agent-based modelling · Life cycle assessment · Decision-making · Natural capital

1 Introduction

Land is a limited resource and as such its use generates trade-off choices for landowners and public authorities who have the responsibility to incentivize and support certain land use choices over others. In this framework, simulation and visualization tools can help stakeholders to understand the possible outcomes of different strategies and select suitable alternatives.

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Although intense research has been carried out and major developments have been achieved in the assessment of the impact of production systems on the environment, the complexity of the models calls for a growing need for software with user-friendly interfaces and visualization capabilities to present the results of the simulations [1]. The final impact of a project relies heavily on the easiness of communication and the accessibility and usability of its results by the target audience and relevant stakeholders.

In the case of complex systems, evaluation of different scenarios is naturally a difficult task due to existence of large amount of simulation outputs. A pre-defined set of performance metrics and a dashboard that summarizes and visualizes them can help users to draw meaningful conclusions and comparisons between scenarios. However, as it is the case for most complex systems, the analysis and visualization of simulation outcomes require a combination of data analysis methods. From the experience of the authors, building a single tool to analyze large amounts of data that includes geospatial information, network analysis, sustainability assessment indicators and financial performance, is a nonnegligible effort, but can significantly help the recipients of a final research product, whether they are researchers or not. With such a tool can be possible to achieve the important task of clarifying the model goals and parameters for people who are not involved in the modeling process task. Furthermore, comparison of different scenarios and effect of changing parameters can aid users in the decision-making process.

As suggested in modern sustainability research, when dealing with human-environment interaction a trans-disciplinary approach is required [2]. To study coupled human-natural systems, agent-based modelling has been gradually accepted as a useful modelling technique [3]. Agents are defined as autonomous entities that react to the stimuli coming from the environment and interact with one another under certain rules that are imposed by the modeler and normally defined after consultation with domain experts and stakeholders. Each of them has an objective that can be defined as optimizing the societal or individual benefit. They are capable of learning, adapting, and changing their behaviors, which end up steering their actions.

In this paper we present the first prototype of a web-based dashboard that estimates the revenue and environmental impacts that a farmer can expect applying a certain management scenario on his/her farm. The environmental impacts are calculated making use of life cycle assessment (LCA) and represent lifecycle-based (not just local) global impacts generated by the farm. Both can then be apportioned to each land patch using a given weighting procedure. Once the revenues and non-local environmental impacts are estimated and mapped, they can be overlaid onto other maps representing outputs of local analysis (e.g., habitat value, ecological connectivity, risk of soil erosion). These latter inform on the local environmental value of the land, complementing the lifecycle-based environmental assessment. The dashboard, together with local environmental analysis, would support a better-informed management of any land plot, based on the positive and negative environmental and economic outcomes of different land uses.

The calculation of the revenues and the environmental impacts is carried out using an agent-based model (ABM) of the farming system (which includes mixed farms, dealing with crops, meat and milk at the same time) coupled with an LCA calculation run on the background of the dashboard which is then used to display pre-calculated results. Future developments incorporating local environmental analysis (e.g., ecological connectivity analysis) will inform about local environmental values of the land patches using indicators and tools such as landscape metrics, connectivity indices, circuit-theory models. The maps thus generated can be easily loaded into the dashboard as it can handle georeferenced files.

In the paper, visualization techniques and technologies behind the prototype are first discussed. The prototype that shows the results from our selected case study is then presented and planned future development are outlined.

2 The Dashboard

The dashboard is created using Django web-framework and its structure is depicted in Fig. 1. It allows to run computations in the backend using other Python libraries that are already integrated into our simulation pipeline. Based on the feedback from project partners and reviewed literature, the dashboard was designed using the components depicted in Fig. 1. The data is stored using PostGIS which has the ability to manage Geographical Information System (GIS) and numerical data in one database. The PostGIS application is available in a docker container to make it compatible for different operating systems. Thanks to Django, we access the database and manipulate the tables with Python's powerful libraries. In the front-end, JavaScript allows to use interactive visualization tools to better investigate the simulation results, as well as the static properties of the farms. The dashboard can currently be used on the most common web browsers (Chrome, Firefox, Safari etc.). All the code is stored in Git and can be accessed by other contributors within the project team which allows further collaboration. The dashboard aims to provide user-friendly insights for farmers, advisors, agencies, and public administrations in terms of agricultural and financial sustainability. Although the development has been made mainly on a web-based portal, a mobile-based application

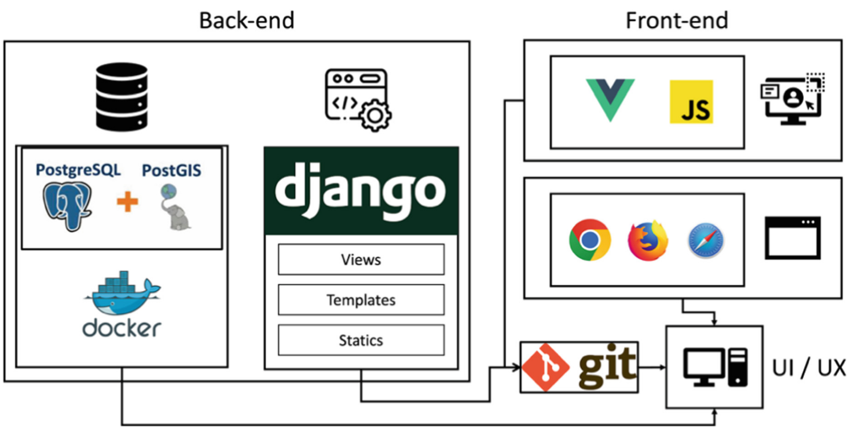

Fig. 1. The back-end/front-end structure of the dashboard.

would be necessary for farmers to make the interaction effortless. It may also be possible to allow other researchers to access the dashboard via application programming interfaces (APIs) when they want to conduct their own research.

The Two-Way Communication Between Farmers and Organizations. In our platform the farmer is the main entity and the agencies will be able to access the farmer's data as long as it is allowed by the farmer. Depending on the nature of their relationship, the agency for example can give recommendations (in case of a consultant) or send reminders (in case of a public agency). The agency will have another version of the dashboard that is suitable for its purposes. Figure 2 shows the different levels of possible users of the dashboard and their motivations to use it.

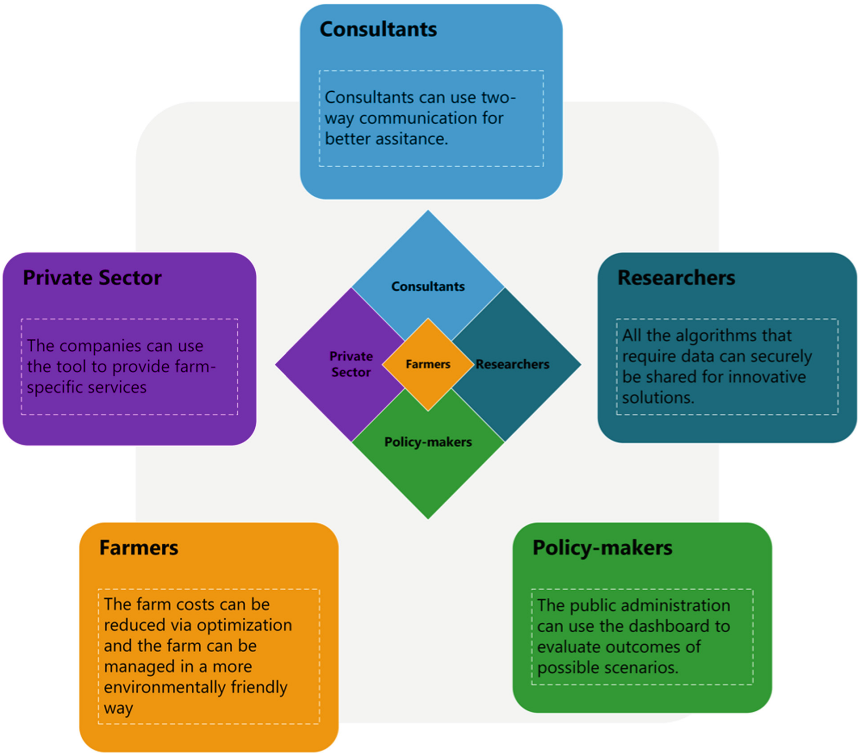

Fig. 2. The possible users of the dashboard and their possible motivations to use it.

The Input from Farmers. Although we mostly use static data, which is the data available in national inventories, one of the major steppingstones for future-work for our research can be the collection of data on a farm level. The classification of crop plantations from Sentinel imagery is possible thanks to computer vision algorithms [4], however the farmers still need to report the crop plantations to the agencies in Luxembourg. They are also required to fill out additional forms, such as grazing calendars, which would allow them to get subsidies. Our tool may allow seamless data-entry for the farmers. Apart from already required and usual data requests from agencies, farmers can choose to enter the real cost and production data to visualize and assess the business from the financial point-of-view. This can even be achieved utilizing the machinery or sensors around the farm, such as milking or feeding robots, wherever and whenever available. All these elements would result in a simplification of farmers' tasks and a fast reusability of up-to-date data.

The Fertilizer Usage and Nitrate Vulnerability. Most farmers are already aware of the nitrogen limits within and along the surroundings of their farms, however with the dashboard it is possible to show the nitrogen constraints on a map based on water body proximity. This information can help them stay below the imposed limits, thus qualifying to get subsidies. There are several subsidy programs in Luxembourg that are based on nitrogen constraints and the imposed thresholds change according to the proximity to ecological protection zones. Based on the provided algorithm for nitrogen excretion from livestock and fertilizer usage for crops, the farmers can see the already released and projected fertilizer input to the soil for a given period. It will also be possible to recommend optimum organic and inorganic fertilizer levels for each type of crop once the soil properties map is incorporated into the model.

The Weather and Climate Forecasts. This information is important for extensive farms, where the farmers let their animals graze outside, depending on the weather conditions. These forecasts can be combined with several other pieces of information such as current levels of soil moisture, grass height, barn temperature and air-quality. Some of these can be made available on the dashboard for the farms where required sensors are available. Figure 3 (left) shows the visualization of the weather forecast in the dashboard for a random commune.

Since the calculation of the revenues and the environmental impacts is based on an ABM, the mutual interactions of the agents are taken into account, as explained in [5].

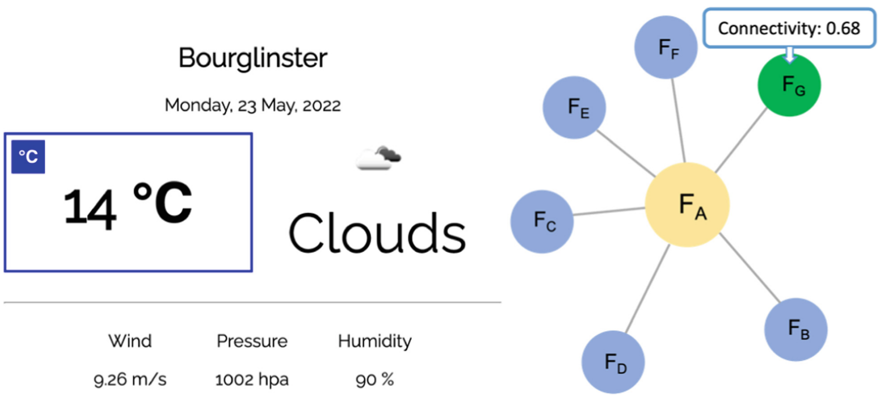

Fig. 3. (Left) The weather information for the farm's location. (Right) The connections of Farmer A (F_A).

Figure 3 (right) shows the visualization of the connection of a given farmer to the other agents in the network.

The Overview of Simulation Environment. The farmer agents act on the same fields throughout the simulations. This means that the farm and field boundaries do not change. The geospatial data that includes those boundaries is stored in a PostGIS database. It is read by GeoAlchemy2, Python object relational mapping (ORM) library for spatial databases, and then visualized with Folium, another Python library to create interactive maps. The users can interact with the map to see the crops planted and harvested in a given field throughout the simulation. Figure 4 shows a screenshot of the dashboard window where a selected farm and the life cycle impact assessment (LCIA) scores related to it can be visualized. Currently we are using the ReCiPe LCIA method [18] to calculate the impact scores, but any other existing method can be easily used in future updates of the tool. On the left-hand side of the figure one can see that each single field belonging to the farm (i.e., each polygon for which information is known at the cadaster level) is visualized.

Fig. 4. (Left) The fields that belong to one farm. The user can interact with the map to visualize the field attributes. (Right) Life-cycle impact scores for a given farm in the span of 10 years (chosen as time horizon of the simulation to obtain pre-calculated results).

Holdings' Financial Balances. The 2D charts that show the monthly and yearly finances of each farm holding allow users to see the seasonal trends in every cost and revenue category. Every time a scenario is simulated with the ABM, this has implications on different categories. Lower production does not necessarily mean less profit for the farmers, due to reduced costs and, in some scenarios, the increase of certain subsidies from the government. After each simulation run, the value of each cost and revenue item is stored in CSV files. Then they are curated using the Python data frame library Pandas and visualized using Charts.js. In a future version of the dashboard, we plan to visualize the results of sensitivity analysis on input variables, such as the amount of subsidy given for a particular activity.

Life-Cycle Impact Assessment (LCIA) of Each Holding. The agricultural activities generate impacts that have short- and long-term effects on the environment that must be monitored carefully by every stakeholder in the sector if an emission reduction strategy is put in place. LCIA allows to quantify these impacts and take necessary actions to mitigate the emissions that are the reasons behind them. In our model, the Brightway2[1] LCA library is used. It was created to enable modelling functionalities that can go beyond traditional LCA software. In particular, using Brightway2 it is possible to seamlessly connect LCA calculations with other simulation engines (in this case the ABM). With Brigthway2 the so-called life cycle inventory (LCI) background data that reside in a LCI database can be recalled automatically and used (together with the foreground data that contains the crop and animal outputs) to calculate the LCIA scores during the simulations. Brightway2 is integrated in the dashboard, in a way that the users can select the impact assessment method they want to adopt for impacts calculations and the impact categories they want to monitor.

The Network of Agents. One of the crucial mechanisms in agent-based modelling is the interaction and information exchange between the agents. In our model, classes of agents were first created according to their risk aversion orientation and their geographical position, as described in [5]. The farmer agents that belong to the same risk aversion class or the ones who are geographical neighbors of one another are considered as connected in a network analysis sense. Each farmer and its connections are shown in a way that their attributes evolve over time (for instance age) and due to information exchange (e.g., environmental awareness).

Assessment of Finances and LCIs at Country-Level. Since each farmer agent acts upon the land belonging to its single farmland, this latter is the reference spatial unit we can assess in terms of economic value and environmental impact generated. However,

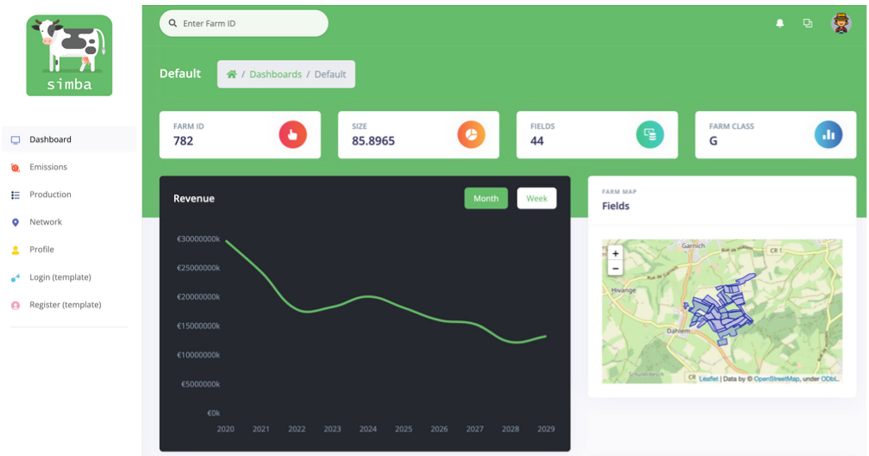

Fig. 5. The graph showing the trend of the net revenue of the farm over ten simulated years.

[1] https://brightway.dev/.

the policymakers have the interest to make assessments at regional level. Therefore, the dashboard allows to show the aggregated result scores as a drill-down weighted treemap with three levels, i.e., farm, commune and canton. The users can choose to visualize the farm outputs, revenues, costs or impact scores. Figure 5 shows a screenshot of the window used to visualize the net revenue of the farm over ten years as resulting from a pre-simulated scenario.

3 Case study: Farmland Revenue Generation and Impact Assessment

The dashboard prototype was used to visualize the results of a scenario which has the objective of reducing stocking rates (i.e., the density of animals per ha) throughout Luxembourgish farms. The scenario was simulated for a time span of 10 years with time steps of one month. The simulations are repeated 50 times and the results are averaged to consider the intrinsic variability induced by the random choice of certain parameters (such as behavioral attributes of a farmer, the allocation of fields of a farm, seeding and harvesting months of crops, etc.). The objective in this case study was to observe the change in the herd structure of the farms over time, and its simultaneous impact not just on the farm finances, but also on the environment. Reducing the stocking rates can help the agricultural sector to mitigate its greenhouse gas emissions. A reduction on stocking rate would be certainly pushed by a reduction of meat and dairy products' consumption coming from consumers due to change of their dietary habits. Less animals would mean less direct costs (like feed imports), as well as an improved soil quality. Within this context, certain subsidies are set for different levels of nitrogen input reduction in Luxembourg. At every year *n* of a simulation, an agent checks the nitrogen emissions into the soil caused by the herd at year *n-1*. If the objective level that was set based on the livestock unit area is exceed, then the agent chooses to get rid of the less efficient animals from the herd. Once this decision has been taken, the production of current year *n* is calculated and the corresponding revenue generation, as well as the emissions, are recorded. Afterwards, the selected animals are sent away from the herd (sold or slaughtered).

The emissions tab on the sidebar allows to see the evolution of the emissions throughout the simulation. If a farmer is logged in, the historical and simulated emissions are shown on the emissions tab; when the user is connected using administrative credentials, the country or regional level emissions are made available. In addition to monitoring the levels for whole country, we also use weighted treemaps [6], along with real maps of subregions, to see the impacts in more detail. In Fig. 6 (Right), impacts on human health (expressed in the unity DALY, which stands for *disability adjusted life years* [7]) generated by emissions due to crop and cattle farming are given per each canton of the country. The same representation is provided also as a treemap (Fig. 6 Left). The weighted treemap algorithm allows to represent the original polygons as rectangles, while respecting their boundary and topological relationships. As expected, the agricultural practices cause more emissions in northern Luxembourg than in the southern part of the country, since most farms are located in that region. The dashboard also includes the *drill-down* version of the weighted treemap, where the users can look at the treemap that is built based on a selected variable (i.e., size, production, number of livestock, impact score, revenue) in cantons' view at the highest level. By clicking on any canton, one can visualize the communes in that canton in a similar fashion. Finally, the farms in a selected commune can be visualized in the lowest level of the drill-down treemap. Figure 7 shows an example of drill-down treemap, that is built using the size of each region (canton, commune or farm). In this example, the user clicks on the canton of Esch-sur-Alzette canton and then on the commune of Pétange, to display the farms present in that area.

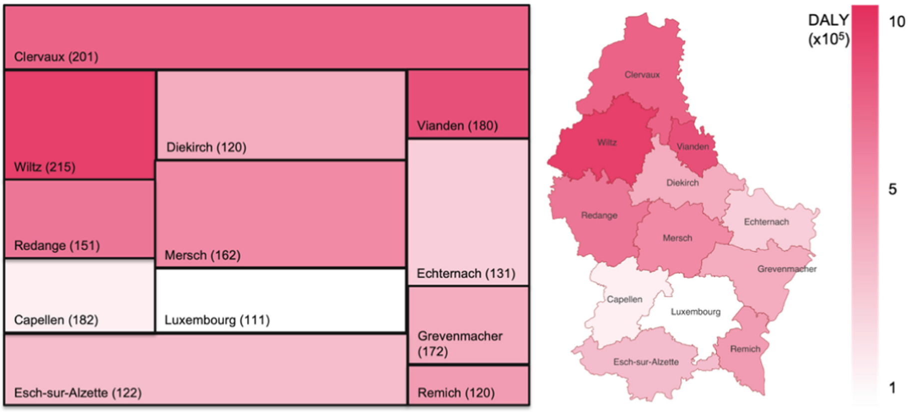

Fig. 6. Left: the weighted treemap that shows the average human health impact over 10 years of simulation and 50 different iterations. Right: the same information visualized as a traditional geographical map.

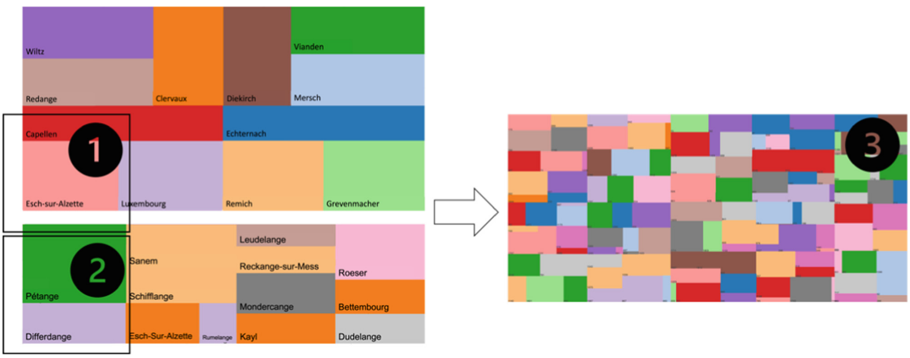

Fig. 7. The drill-down treemap implementation of geographical boundaries of Luxembourg.

4 Discussion and Conclusion

The paper presents the first prototype of a web-based dashboard that can be used to assess the economic and ecological impacts of land transformation. The direct economic value of the land patches used as cropland or pasture (i.e., the net revenue for the farmer, without considering the cost of environmental externalities) is pre-calculated using a hybrid ABM-LCA model that mimics the evolution of the Luxembourgish farming system under management scenarios that can be designed upstream. The hybrid model is also used to calculate the environmental impacts of each management scenario (which are then allocated to the single patches) using LCIA indicators [18].

Looking also at future further developments of our dashboard, one important observation we can already make is that land is not only a source of food and material resources for humans (the so-called *provisioning ecosystem services*); it is also a source of regulating and cultural ecosystem services [8]. Among the regulating services, natural, semi-natural and agricultural land support the maintenance of nursery populations and habitats on which plants and animal species depend. Anthropic land transformation (land use conversions) could harm ecosystem functions (e.g., ecological connectivity) that influence habitat maintenance. For example, the transformation of certain patches of land that are in strategic positions for species movement or the creation of human artifacts (e.g., agricultural fences, roads), beyond direct habitat loss, could result in a loss of ecological connectivity which also ends up influencing species survival negatively [9]. To assess the impacts in terms of habitat loss and ecological connectivity, indicators and tools such as landscape metrics, connectivity indices and ecological connectivity models have been developed. They are based on different approaches, spanning from least-cost path analysis [10], to circuit theory [11], matrix theory [12], agent-based or individual-based modelling [13], network analysis [14] and other techniques. A wider overview on ecological connectivity approaches and models can be found in [15].

Given the importance of these ecological functions of land, the next step we plan for the dashboard is the addition of a further geospatial layer that represents the value of each land patch in terms of their contribution to habitat maintenance. For example, as proposed in [16], using as input data species distribution models of Luxembourg developed in [17], ecological connectivity analysis can be easily developed, informing on referred routes of movement of certain species (e.g., endangered or protected ones). In this way the relevance of specific land patches to enhance ecological connectivity of species populations can be evaluated. As another alternative, a combined use of connectivity indices such as the Integral Index of Connectivity (IIC), the Betweenness Centrality (BC) and the Probability of Connectivity (PC), could be considered to estimate the patches with the highest value for ecological connectivity (also applied in [16]). If these key patches are close to protected areas and are currently used as cropland, the dashboard could be used to calculate the net revenue that the farmers can associate to those patches and therefore determine a value of a fair compensation that they should be granted if they are requested to hand over the ownership of those patches to the public administration that can then convert them into protected areas. We will therefore integrate the calculation of the value of each land patch from the habitat connectivity point of view, using landscape metrics and connectivity indices (for examples using tools such as Conefor [19] or Fragstats [20]). This will allow the identification of the most important patches that can then be selected as priority (key patches) to inform ecological planning or the definition of biodiversity action plans. When these key patches fall within existing farms (where they are used either as cropland or as pasture) the dashboard will then allow also to determine the expected monetary compensation that the farmers who own these patches should receive for the production capacity loss they would incur to reduce the pressure on the land (i.e., have a less intensive cultivation), if these patches become part of an environmental stewardship program to protect biodiversity and are therefore converted into protected areas.

Apart from technical perspectives and objectives of this tool, it is worth noting that the development procedure should be integrated with users' feedback along all the stages. That means working with agencies and farmers who understand the necessities of digitalization in agriculture and provide valuable feedback. Understanding the needs of farmers from different ages and whose farms differ in size helps building a helpful tool that reflects the characteristics of the farm system of the given territory. Moreover, the agencies that would be using this tool may decide on what to emphasize or communicate strongly to the farmers via this tool during the development phase which would possibly increase their motivation.

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