Change Detection and Analysis of Landscapes Based on a Spatio-temporal Landscape Information Model

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Abstract: For the analysis of landscape changes, methods based on remote sensing data are often used. Although these methods now use Object-Based Image Analysis (OBIA) to go beyond a pixel-by-pixel comparison of images, remote sensing cannot capture the change in important semantic information that are not physical in nature, but required for planning processes, such as changes in land ownership or changes in zoning regulations. In contrast to the methods based on remote sensing data, this paper presents a novel method that enables large-scale change detection, documentation, and analysis at the level of individual landscape objects. The presented method is based on a spatio-temporal landscape information model. Even though the input data for the model are annual extracts of public authority information systems, the spatio-temporal representation of the data goes beyond the familiar "snapshot or object-lifetime approach" in Geographic Information Systems (GIS) by keeping the identity of landscape objects stable over time and tracking the evolution of each individual object. In addition to the conceptual model, which is specified using the Unified Modeling Language (UML) and the ISO 191xx family of standards, the paper will show how this approach can be implemented based on an object-relational spatial database system. Several use cases demonstrate the benefits of the approach for planning.

Keywords: Changes in agricultural landscape, object relational model, landscape information modeling, spatio-temporal database, object-based change detection, land consolidation, landscape planning

1 Introduction

Landscapes are constantly changing. One of the biggest challenges has always been how to observe, document and analyze the changes in the easiest and fastest way without losing information. To obtain, interpret, monitor and analyze land use and land cover changes different techniques and methods have been developed. The various methods and techniques differ from each other due to their advantages and disadvantages and are used for different purposes. The development of satellite and remote sensing technologies resulted in the development of a wide range of methods for detecting environmental changes based on satellite images and airborne imagery. MAS (1999), KERR & OSTROVSKY (2003), and ZHU (2017) provide a general overview of these methods. CHEN et al. (2012) provide an overview, focused on object-based change detection. Dependent on user needs, it is important to note that remote sensing data does not provide all the information that may be required, as mainly land cover information can be obtained from such imagery, whereas important semantic information for landscape planning, such as ownership or zoning regulations cannot be detected. Consequently, an additional source of information should provide supplemental information

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on land use and land cover data for further analysis, visualization, and representation. A GIS providing this additional semantic information should balance the limitations of the change detection methods based on time series of remote sensing images, which should be recognized as a major advantage by many users of land use and land cover information (ANDERSON 1977).

However, many GIS-based methods use a "snapshot or object-lifetime approach" that does not explicitly represent change and therefore does not allow for a comprehensive analysis at the level of individual landscape objects any more than a pixel-by-pixel comparison of classified remote sensing imagery. The approach developed by MACHL (2021) and described in this paper overcomes the limitations mentioned above by an object-oriented semantic information model, which includes an explicit representation of state changes and cross-object transitions over time for individual landscape objects. The model is enriched with datasets from the Agricultural Administration and the State Mapping Agency. The research questions to be addressed in this paper are:

1. How should the information model be designed in order to represent the cultural landscape in an application-neutral and cross-scale spatio-temporal manner, enabling a variety of analyses in landscape planning?
2. How can the evolution of individual landscape objects as well as cross-object-transitions be represented in an object-oriented information model and in a spatio-temporal database system?
3. How can changes in individual objects be aggregated to comprehensively represent changes in the cultural landscape?
4. Which applications do the developed methods fit for and which advantages do they have?
5. What distinguishes this method of landscape change analysis from other methods?

2 LandModell: A Semantic Model of the Cultural Landscape

The above research questions will be investigated based on the semantic model of cultivated landscape developed in the project LandModell at the Technical University of Munich, Chair of Geoinformatics. The aim of the research project LandModell was to design, implement, and establish a system for cross-scale, state-wide, and continuous monitoring of the agricultural landscape, that provides an explicit representation of the evolution of objects and temporal relationships between objects. By defining relevant object classes, attributes and relations, the semantic geospatial model allows the agricultural landscape to be represented as a complex system of interacting and changing elements. Thus, the data model provides a solid basis for in-depth analyses, e. g. for the detection, documentation and description of Spatio-temporal change processes. In the design of the data model, special attention is given to wide applicability for various scientific questions, for example in the fields of agroecology (e. g. erosion, climate gas balancing or biodiversity) or agricultural economics (economic evaluations of parcel structures, selection, of ecological priority areas). The model has been used for several applications like planning agricultural road networks (MOSHREFZADEH et al. 2020) or the parametric description of land parcels (MACHL et al. 2013). An overview of the semantic model and related tools is given by MOSHREFZADEH et al. (2020).

3 Spatio-temporal Modeling of Landscape Objects

The use of agricultural land for the expansion of residential, industrial, or commercial areas, as well as the development of concepts to reduce land consumption, is increasingly becoming the focus of public discussion (DLKG 2016, DLKG 2017, DLKG 2021). Providing information on historical land-use changes and applying analytical techniques can be used to address land-use transitions. Changes in the landscape and various regional challenges are associated with demographic growth (MURTHA et al. 2019). Various systems and tools have been developed to detect, monitor, and plan landscape changes and rapid urbanization not only in urban but also in non-urban areas, and to identify anomalies in agricultural areas.

According to STEINITZ & ORLAND (2021), in landscape design it is necessary to recognize the past changes, to be able to prescribe them, and know the limitations in order to make adequate plans for the future. Also, ANDERSON (1977) stated that for having the ability to operate land information, it is necessary to have information about the historical, existing, and changing land use over time. Against the background of these requirements, a Spatio-temporal model of the cultural landscape must take the following aspects into account: For each landscape object, its lifetime and its genesis (cross-object transitions, i. e. predecessors and successors of an object) must be represented. The following sections describe our general approach for modelling these aspects and also some key elements of our information model as UML class diagrams.

3.1 Modeling of the Object Lifetime

Figure 1 shows a hybrid scheme for the explicit mapping of object lifetimes (symbolized via Spatio-temporal bodies of volumes) and cross-object transition relationships between objects over time (represented as red transitions). *Figure 1* is illustrating the concept by using two-dimensional geospatial objects. In the example, objects A, B and C exist at time t_0. While the lifetime of object C extends beyond t_4, the lifetime interval for objects A and B ends at time t_2. At the same time t_2 the lifetime interval of object D begins, which extends to t_3. At time t_3, the lifetime of objects E and F begins, which exist from t_3 until beyond t_4.

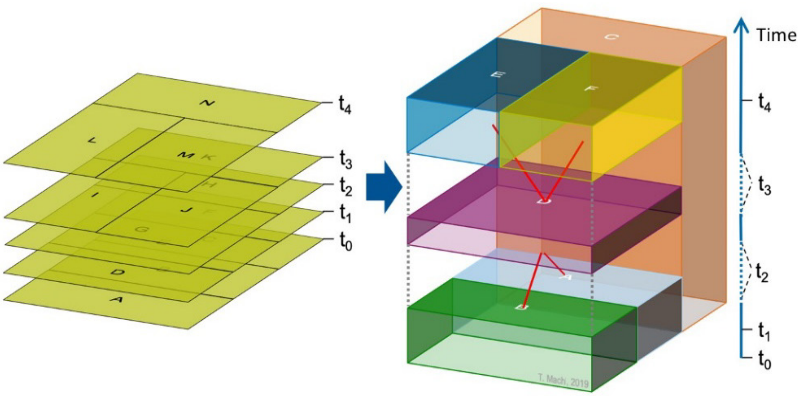

Fig. 1: From snapshots (left) to object lifetimes and cross-object changes over time (right) (MACHL 2021)

3.2 Modeling of the Cross-Object Transitions

Cross-object transitions between individual elements over time must be represented in the form of transition relationships and provided with a corresponding semantic description in order to make them accessible for analysis. The semantic description includes e. g. the time of appearance or the type of cross-object change relationship (e. g. subdivision or merging), as well as a description of the reallocation of individual geometry fragments. The transition relations do not have a temporal extension but only a position along the time axis. The transitions are explicitly recorded and shown in Figure 1 (MACHL 2021). This allows the tracing of the historical events for each geospatial object and each geometric component of the object, including its creation and destruction. The fate of each object has been tracked and represented as long as it exists in the landscape. This means that with this structure it is possible to drill down to the very individual changes of the individual landscape objects and track the fates along with history.

In order to model and describe such transitions, the fates of individual geometry fragments must be known. For each geospatial object and each geometric component of the object, the history can be tracked, including its creation and disappearance. The basic concept is illustrated in Figure 2 using the example of the transition between the semantic objects A and B at time t_n into objects C and D at a later time t_{n+1}. The transition relationships between semantic objects are symbolized in the form of red connecting lines, the fates of geometry fragments are symbolized as blue connecting lines. Note, that in our landscape model geometries are spatial objects representing the geometry of the semantic landscape objects. In the example, the semantic object C emerges from the semantic object A as the result of a subdivision. Accordingly, the relationship between A and C as well as the fate of the geometry fragment A_1 can be classified as a subdivision. At the same time, object B is merged with a partial geometry of object A to form the new object D. Thus, the objects A and B are successor objects of D, whereby this succession relationship is valid for the geometry fragments A_2

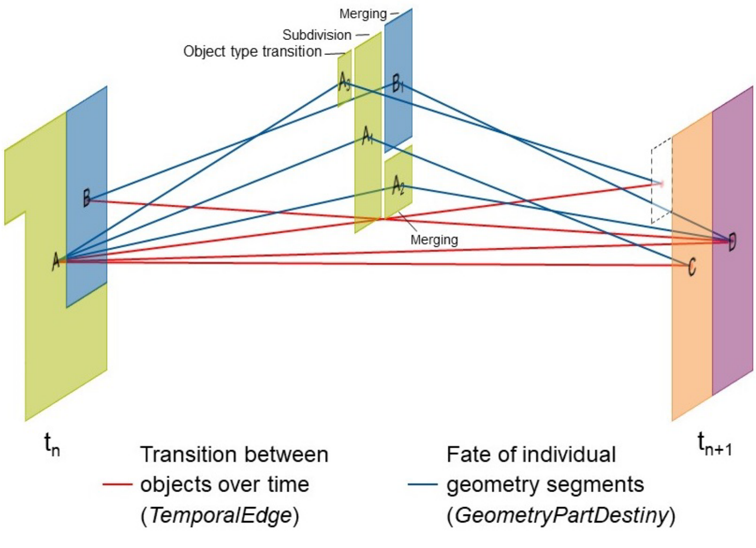

Fig. 2: Concept for mapping cross-object transitions between objects at time t_{n+1} (adapted from MACHL 2021)

and B_1. Both geometry fragments A_2 and B_1 are merged into the new semantic object D. At t_{n+1}, the geometry fragment A_3 is no longer part of a semantic object of the same type as A, B, C or D. For this geometry fragment, a transition to another semantic object type takes place, e. g. a transition from an agricultural parcel to a traffic object.

The lifetime of individual elements of the cultivated landscape, cross-object transition relationships, and also changes in the state of objects are derived from sequences of annual snapshots of the data sets provided by different authorities. A fundamental challenge of this work is therefore the retrospective derivation of object lifetimes, state changes, and cross-object transition relationships between objects over time from sequences of time slices of heterogeneous data sets.

3.3 Object-Oriented Information Model

In geoinformatics, the modeling language Unified Modeling Language (UML) has become particularly popular as a graphical notation and formal description of conceptual data models. In the world of geoinformatics, standards and norms are an essential basis for the interoperability of different system components, the compatibility of geoinformation, and the provision or exchange of geoinformation via spatial data infrastructures. The standards of the ISO 191xx family are an important basis for the interoperable modeling of geoinformation. Our information model applies these standards, whereby the general structure of our information model is based on the successful modularisation concept of the international OGC standard CityGML.

Our model consists of a core module and twelve thematic modules. Each of these thematic modules deals with different aspects of the cultivated landscape, such as *AgriculturalLandUse*, *Farming, LandConsolidation, SettlementArea* and *Agricultural Transportation*. Basic concepts of the model are described in the core module. The Figure 3 shows the concept for mapping the temporal and spatial topology of the mapped objects. The Figure 3 describes the concepts for tracking changes over time. The Figure 4 shows the basic classes and the fundamental aggregation hierarchy of the model. The abstract class *AbstractLandObject* includes attributes for representing the object lifetime within a dataset (attributes *creationDate* and *terminationDate*) and within the physical reality (attributes *validFrom* and *validTo*). This corresponds to the concept of bitemporal representation of all object states (SNODGRASS & AHN 1985).

According to the concept of semantic enrichment of objects by the results of analysis methods, the class *AbstractLandObject* also has an association to the class *AbstractAnalysisResult*. Besides the base classes and the basic associations between them, the core module describes the spatial and temporal-topological relationships between elements in the form of a graph structure. With the abstract class *InterFeatureConnection Graph* the core module offers the possibility to represent topological relations between objects, which can be spatial (*SpatioTopologicalInterFeatureConnectionGraph*), as well as temporal (*TemporalInterFeatureConnectionGraph*), in the form of a graph. The representation of the temporal transition between two objects as a sum of individual change steps is realized via the attribute *transitionSteps*. The core module also contains concepts for mapping attributes with time-limited validity, as well as time-line attributes. Semantic description of transition relationships between object over time are described in the *TemporalEdge Class.* The possible transition relations between objects over time are described in the the *CodeList TypeOfChange*. Transition relationships between objects can be divided into the following four types of transition relationships: fusion, division, update or transition to another object type (Figure 4).

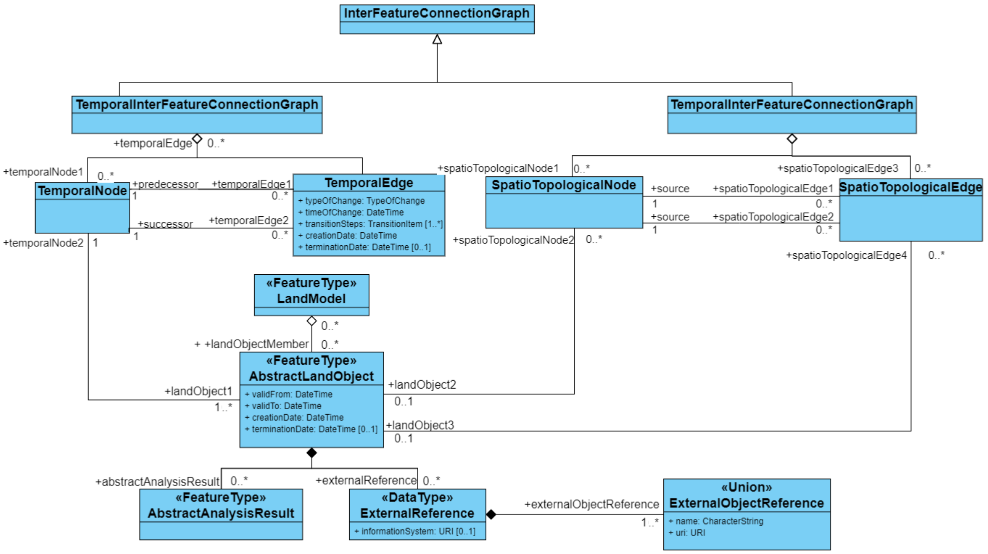

Fig. 3: UML class diagram of the core module (adapted from MACHL 2021) (1)

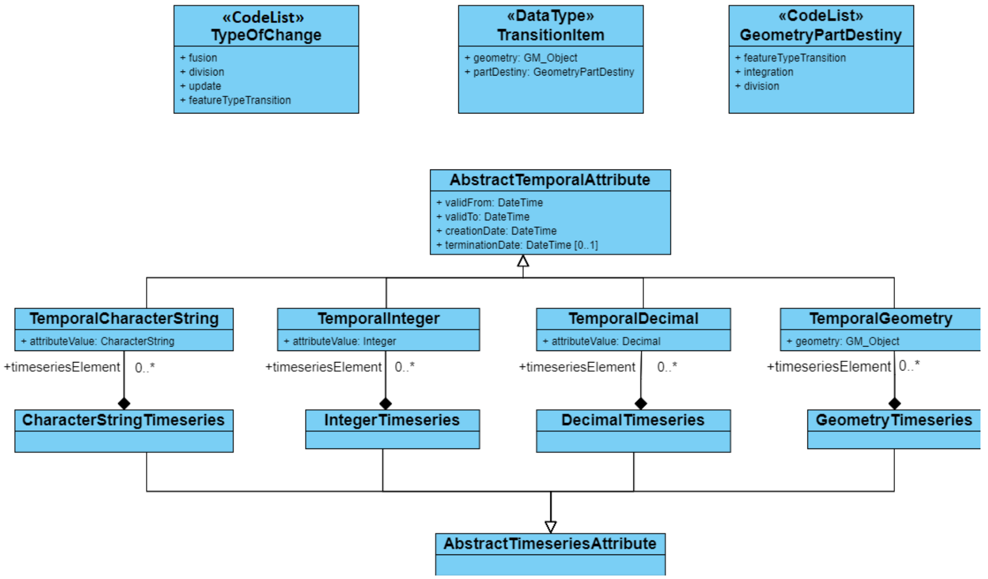

Fig. 4: UML class diagram of the core module (adapted from MACHL 2021) (2)

The Figure 4 shows the classes *AbstractTemporalAttribute* and *AbstractTimeseriesAttribute* with their respective specializations. These classes make it possible to represent properties of semantic objects as time series and thus to store and reconstruct current and historical states of the objects. The Figure 5, which is an excerpt from the thematic module *AgriculturalLandUse* of our model, illustrates the concept of time series attributes of semantic objects. The class *AgriculturalParcel* has an attribute crop, which is of type *CropTimeseries*. The UML diagram further shows that *CropTimeseries* is a specialisation of the *AbstractTimeseriesAttribute* class and therefore a collection of individual objects of type *TemporalCrop*. Finally, the class *TemporalCrop* for representing the individual crop values is a specialization of the class *AbstractTemporalAttribute*, which allows a temporal validity range to be specified for each attribute value.

In this way, it is possible to store for each agricultural parcel in which period which crop was cultivated. Thus, for example, analyses of crop rotation for an individual agricultural parcel or the spatio-temporal concentration of specific crop types are possible.

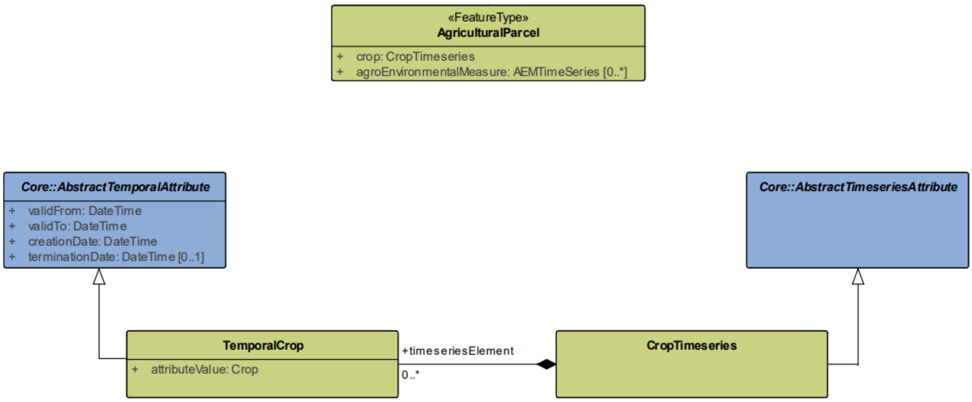

Fig. 5: Excerpt from the thematic module AgriculturalLandUse (adapted from MACHL 2021)

4 Implementation of the Model Using an Object-Relational Database System

The advantages of spatial and temporal database systems have been recognized in many sectors (RODDICK et al. 2004). Modelling of spatial changes with a recording of time slices, snapshots, or object- and event-oriented models is challenging (GANTNER et al. 2013). Since our information model is capable of representing the evolution of individual landscape components and perceiving cross-object transitions over time using an explicit, spatially, and semantically detailed representation, we had to find an object-relational data structure that is both able to cope with these complex structures and able to efficiently store and query large data volumes (compare Table 1 in section 5), rather than using a snapshot or object-lifetime approach as it is often used in Spatio-temporal GIS.

Our database schema is based on the PostgreSQL database management system with PostGIS extension and is the result of a mapping of the object-oriented concepts described in section 3.2 onto the object related concepts provided by PostgreSQL/PostGIS. In the object-relational database schema, packages are mapped as schemas – the name of the schema corresponds to the package name of the UML diagram. The classes (abstract and non-abstract classes) in each package are mapped as tables within the schema. The names of the tables are identical to the names of the corresponding class. The attributes modelled in the classes – as long as they do not have time-variable values – are mapped in the form of columns of the corresponding table with corresponding data types. The full UML diagram as well as the complete database schema is available from (MACHL 2021).

The time-variable attributes are represented for each object type and for each attribute as independent tables belonging to the same schema as the table representing the object type. Figure 6 shows the SQL expression for generating the master table of all time data series attributes within the information system.

```
CREATE TABLE "Core"."AbstractTemporalAttribute"
(
    oid character varying NOT NULL,
    "creationDate" date,
    "terminationDate" date,
    "validFrom" date,
    "validTo" date,
    "id_ReferenceObject" character varying,
    CONSTRAINT "pk_TemporalAttribute"
      PRIMARY KEY (oid),
    CONSTRAINT "check_terminationDateGreaterThanCreationDate"
      CHECK ("terminationDate" >= "creationDate"),
    CONSTRAINT "check_validToGreaterThanValidFrom"
      CHECK ("validTo" > "validFrom")
);
```

Fig. 6: SQL expression for creating the Core.AbstractTemporalAttribute table (MACHL 2021)

The individual components of the complex data type for mapping time series are shown as columns of the corresponding table. In addition to a unique identifier, each of the attribute time series tables contains attribute time series according to the semantic model with the attributes *creationDate* and *terminationDate* or *validFrom* and *validTo* to keep the information on the temporal validity of an attribute value within the dataset or the physical reality respectively (bitemporal data storage). The reference of the given attribute state to the respective object is realized in the form of a foreign key reference to the primary key of the respective reference object. Additional properties of the relationship are mapped as a column with a corresponding data type. In addition to a unique identifier, the table has columns for mapping the temporal validity of the relationship within the dataset or the physical reality. In the database schema, temporal transitions between objects are modeled as a separate table for each mapped object type, so that a corresponding table for each object type establishes a relationship of the objects over time. Deleting the object leads to the removal of all referenced attribute entries (MACHL 2021).

The annually updated data are compared geometrically and thematically with the already imported data. Newly created objects are entered into the database. If changes in attributes are detected for objects, that already exist in the database, they are updated. If no changes are detected for objects and attributes, only the validity value is updated, which corresponds to an extension of the object's life time.

5 Data Sources

In many research works on detecting landscape changes, it is found that remote sensing data is the major source of information. From raster-based data sources and their classification, different methods are used to determine different values for each raster cell (CHEN et al. 2003; BAO et al. 2020; LISTNER et al. 2011; MAS 1999). Based on the same values in raster cells, polygons can be defined and the generated vector objects can be used for further analysis. Comparison of the data obtained from the raster data allows to detect changes. However, there is no guarantee that adjacent raster cells with the same or similar values actually form an object with meaning for a specific application, for example an agricultural parcel in the real estate cadastre.

Since our Spatio-temporal information model relies on meaningful objects with stable identifiers instead of using remote sensing data, we focus on objects from diverse cadastres and topographic information systems. As input for our model, we use yearly snapshots from these sources until now for a period of eleven years. A single snapshot represents a complete copy of a dataset at a specific instant of time. Integration into the system is done through automated geoprocessing workflows using the software package FME. The data from the Agricultural

Table 1: Overview of the imported data

	Object type	**Number of imported objects/ elements**
Agricultural land use	Farmer Blocks	1.9 million elements per year
	Agricultural Parcels	2.2 million elements per year
	Farms	105 000 elements per year
Transportation routes	Road center lines	1.6 million objects per year
	Lane center lines	0.2 million objects per year
	Track center lines	1.4 million objects per year
	Footpaths	0.2 million objects per year
Cadastral parcels	Parcel boundaries	10.6 to 10.8 million objects per year
Land use/land cover	Vegetation object type group	3.0 to 3.3 million objects per year
	Settlement object type group	1.3 to 1.4 million objects per year
	Transport object type group	1.4 to 1.5 million objects per year
	Waterbodies object type group	0.3 to 0.4 million objects per year

Administration and the State Mapping Agency (LDBV – Landesamt für Digitalisierung, Breitband und Vermessung) and the *Bavarian State Ministry of Food, Agriculture and Forestry* (BayStMELF) provide the basis for the development of the information system. Our system integrates data from the following sources covering the entire state of Bavaria, Germany: *Integrated Administration and Control System* (IACS), *Official Real Estate Cadastre Information System* (ALKIS – *Amtliches Liegenschaftskatasterinformationssystem*), and *Official Topographic Cartographic Information System Data* (ATKIS – *Amtliches Topographisch-Kartographisches Informationssystem*) data. The basis for the calculation of transport paths between farms and all of their individual farming parcels are road center lines taken from the *Base Digital Landscape Model* (Base DLM) of the LDBV. The accurately surveyed and described parcel boundaries and geospatial data of actual land use originate from ALKIS.

6 Use Cases

The variety of objects and attributes integrated into the database over the years allows its use for different applications and analyses. The data can be used to calculate diverse indicators for the evaluation of quality, e. g. for the economic and ecologic characteristics of a particular rural area and their changes over time. The following sections present two use cases and analysis results, that require change detection and analysis based on individual landscape objects. Both use cases originate from planning processes in the area of land consolidation.

6.1 Visualisation of Regional Anomalies – Using Heatmaps

The aim of land consolidation is to improve production conditions in agriculture and forestry and to promote general land development through measures such as the reorganization of land ownership in a given area (BAYSTMELF 2019). Identifying areas where many agricultural parcels are merged to form larger parcels is therefore of interest to planners in the field of land consolidation. In terms of the semantic model described above, this means identifying areas where there is a high frequency of "merge" type changes (cf. Figure 2) in Land Parcel objects. Note that such changes cannot be detected from Remote Sensing.

The parcels represent the transition from agricultural land to transport and settlement object type are filtered, as well as their areas such that a heatmap can be created. For the visualization of the heatmap, the software Quantum GIS 3.16 was used. The database can be connected directly to the software, which is more efficient than working with exported files.

An appropriate method for visualizing these changes based on their spatial distribution is the heatmap (also known as kernel density map). As the data model has a geometric component, it is possible to aggregate the data based on changes and show irregularities that have occurred over the years. The following heatmap shows agricultural parcels merges between 2017 and 2018 in Bavaria.

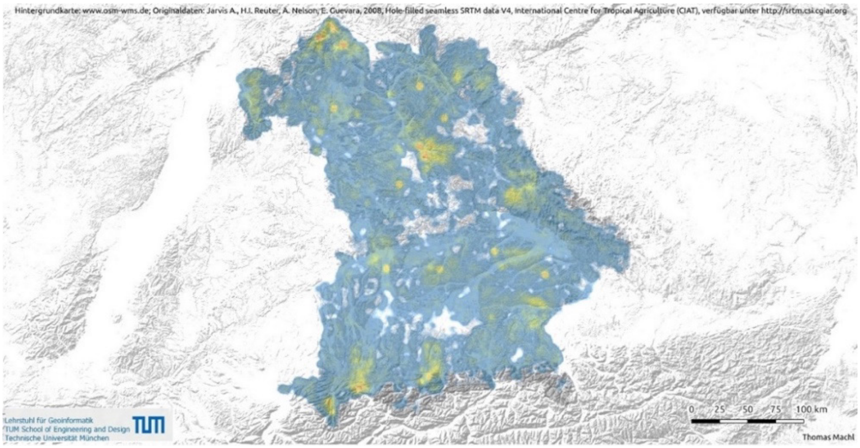

Fig. 7: Heat map of merging agricultural parcels consolidation of ownership between 2017 and 2018 (MACHL 2021)

Another use case that is relevant to environmental monitoring in general and climate change research in particular is to study the loss of agricultural land due to settlement and infrastructure development. For the observed time periods, the actual usage for each parcel is known. The following heatmap shows the aggregation of changes from the object type "agriculture" to the object types "transportation" and "settlement" between 2016 and 2020 in Bavaria (Figure 8). Using such visualization, it is possible to observe regional irregularity based on aggregations of individual changes in the landscape.

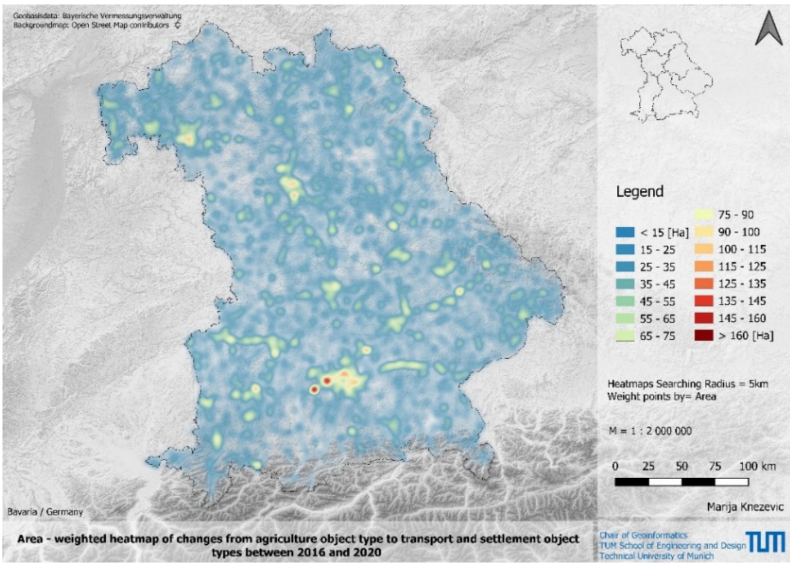

Fig. 8: Area-weighted heatmap of changes from object type "agriculture" to object types "transport" and "settlement" between 2016 and 2020

6.2 Indicators for Describing the Effectiveness of Land Consolidation Procedures

In order to prove the effectiveness of land consolidation procedures, various indicators can be calculated based on our landscape information model. Semantic enrichment of objects with their identities enables the creation of indicators that help in the evaluation of the process of land consolidation. For this purpose, the state of the agricultural landscape before a specific regional land consolidation procedure is compared with the state after the procedure has been completed.

To evaluate a successful land consolidation, three hypotheses were formulated:

- The number of parcels is decreasing, the average size of the parcels is increasing
- The shape of the plots improves in terms of farming management
- The farm-to-field transport distances are becoming shorter

One of the aims of land consolidation is that after consolidation the number of parcels decreases and the surface area of the parcels increases in order to make the cultivation more efficient. This is shown in Figure 9 for a specific area where a land consolidation procedure has taken place. On the graph on the left, it can be seen that there were 744 parcels in 2018 and that there were 583 parcels in 2020 after the land consolidation. In addition, the average size of parcels in 2020 is larger than in 2018, as expected. In addition to the size of the agricultural parcel, its shape is also crucial for agricultural use. Therefore, after land consolidation is carried out, the shapes of the individual agricultural parcels should have been improved. For each parcel, different shape indicators are calculated and included as an additional attribute of the parcel in the database (Figure 10). After the land consolidation not only the number of parcels changed, but also the shape of the parcels.

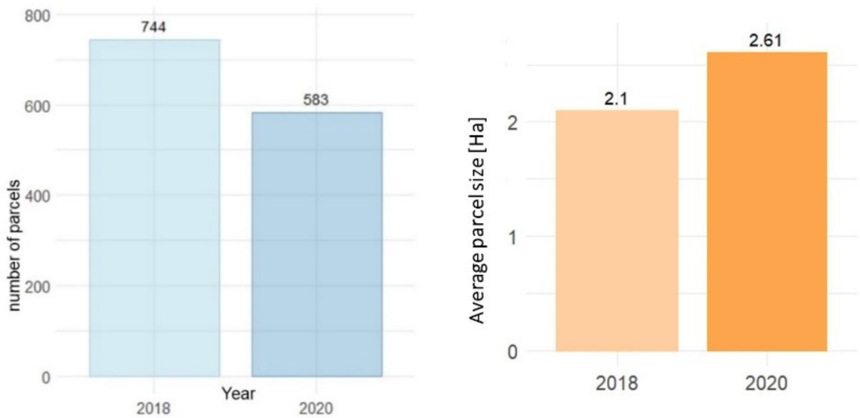

Fig. 9: Charts of the effects of land consolidation based on number of parcels (left) and on average parcel size (right) for 2018 and 2020

Another assumption for successful land consolidation is that the average distances between parcel and farmstead become shorter. It was calculated that the average distance from the parcel to the farm for the land consolidation area was 2.44 km in 2018 and decreases to 1.83 km in 2020. This indicator is calculated precisely on the basis of the individual objects and their relations.

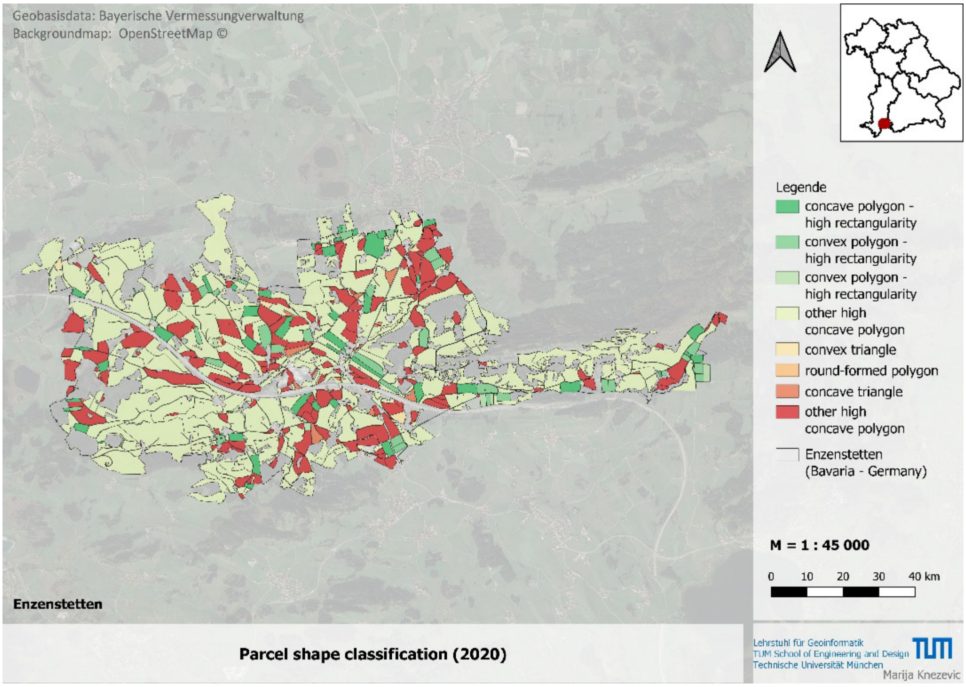

Fig. 10: Parcel shape classification for 2020

7 Conclusion and Outlook

Information about land use is needed to enable appropriate planning, management, and regulation. Changes occur over different time periods, and the question is how to capture and document them to create a digital twin of the landscape.

The approach described here is to develop an information model that explicitly represents landscape change at the attribute level of individual landscape objects and represents the evolution of landscape objects and the relation between them over time. This is achieved by means of a complex object-oriented spatio-temporal schema, using concepts such as time series attributes and time-topological graphs. The information model is specified using the UML modeling language and is based on the international ISO 191xx family of standards. This serves interoperability and allows, for example, to automatically derive a GML-based data transfer format from the model. For the implementation of the monitoring system, the object-oriented information model is transferred into object-relational structures provided by the database management system PostgreSQL/PostGIS.

Based on this implementation, existing object-based spatial data sets, which are constantly updated by the state administration, are processed in such a way that landscape changes are revealed on the basis of the evolution of individual landscape objects and are available for further analyses.

The object-based modeling approach followed in our information model proves to have an advantage over common pixel-based analyses of landscape change based on remote sensing data. This is demonstrated by the described application examples, that use the method for detection of frequent changes as well as for the analysis of the effects of land consolidation procedures. The implementation of the information model proves to be so efficient that area-wide, parcel-specific data sets for the entire state of Bavaria can be integrated and analyzed over a period of 11 years. The developed concept is sufficient for tracking evaluations and changes, as well as for monitoring object history in the landscape environment. Since the unique identifiers of each object are known, it is possible to track the evolution of individual landscape objects over the years, which is not possible by applying remote sensing methods.

Even if the data sets integrated in the described database are not publicly available, the open, standards-based structure of the information system and the implementation based on open source software makes transferability to other regions and to other use cases possible (the publication of the model and the open source software is planned).

The various analysis tools developed on the basis of the information model reveal the great potential of such Spatio-temporal modeling in different sectors. In the future, information on land changes can be used in planning and controlling the consequences of floods, planning the expansion of settlements, planning farms, biodiversity, and other factors that may harm or contribute to the environment and have significant economic impacts.

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