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Multi-Data Approach for remote sensing-based regional crop rotation mapping: A case study for the Rur catchment, Germany

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A B S T R A C T

Spatial land use information is one of the key input parameters for regional agro-ecosystem modeling. Furthermore, to assess the crop-specific management in a spatio-temporal context accurately, parcel-related crop rotation information is additionally needed. Such data is scarcely available for a regional scale, so that only modeled crop rotations can be incorporated instead. However, the spectrum of the occurring multiannual land use patterns on arable land remains unknown. Thus, this contribution focuses on the mapping of the actually practiced crop rotations in the Rur catchment, located in the western part of Germany. We addressed this by combining multitemporal multispectral remote sensing data, ancillary information and expert-knowledge on crop phenology in a GIS-based Multi-Data Approach (MDA). At first, a methodology for the enhanced differentiation of the major crop types on an annual basis was developed. Key aspects are (i) the usage of physical block data to separate arable land from other land use types, (ii) the classification of remote sensing scenes of specific time periods, which are most favorable for the differentiation of certain crop types, and (iii) the combination of the multitemporal classification results in a sequential analysis strategy. Annual crop maps of eight consecutive years (2008–2015) were combined to a crop sequence dataset to have a profound data basis for the mapping of crop rotations. In most years, the remote sensing data basis was highly fragmented. Nevertheless, our method enabled satisfying crop mapping results. As an example for the annual crop mapping workflow, the procedure and the result of 2015 are illustrated. For the generation of the crop sequence dataset, the eight annual crop maps were geometrically smoothened and integrated into a single vector data layer. The resulting dataset informs about the occurring crop sequence for individual areas on arable land, so that crop rotation schemes can be derived. The resulting dataset reveals that the spectrum of the practiced crop rotations is extremely heterogeneous and contains a large amount of crop sequences, which strongly diverge from model crop rotations. Consequently, the integration of remote sensing-based crop rotation data can considerably reduce uncertainties regarding the management in regional agro-ecosystem modeling. Finally, the developed methods and the results are discussed in detail.

1. Introduction

In the context of food security and climate change studies, the optimized management of crops, the forecasting of crop yield, and the modeling of matter fluxes in agro-ecosystems becomes more important (Mulla, 2013; Teluguntla et al., 2015; Thenkabail, 2010). Nowadays, the impact of management strategies on crop yield can be simulated with regional agro-ecosystem models (Giltrap et al., 2010; Resop et al., 2012; Schneider, 2003; van Wart et al., 2013). These models require a large number of input parameters on soil and management properties as well as spatial weather data in a high temporal resolution (Bareth, 2009). One of the key input data for regional agro-ecosystem modeling are spatial land use data including the information on crop types and crop rotations. The latter are of key importance to determine the crop-specific management in a spatio-temporal context within the models (Giltrap et al., 2010; Kersebaum et al., 2007; Lenz-Wiedemann et al., 2010; Lobell et al., 2015; Nendel et al., 2011; Wilson and Al-Kaisi, 2008). However, spatio-temporal data on crop types and on crop rotations at the field level for regional scales are rarely available. One of the seldom examples for the availability of multiannual crop maps are the Cropland Data Layers (CDL) for the Unites States, provided by the National Agricultural Statistics Service (NASS) of the US Department of Agriculture (Boryan et al., 2011). Based on the CDL data, also planting frequency maps for corn, soybeans, wheat, and cotton are provided (Boryan et al., 2014), but spatial data on the actual crop rotations are not included. Leteinturier et al. (2006) conducted a crop

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sequnece analysis for the Wallon region of Belgium based on data gathered in the framework of the Integrated Administration and Control System for European Union member states. However, in most European countries, such information is not available to the general public, due to data protection laws. The lack of this information is a major drawback for regional agro-ecosystem modeling, since large uncertainties concerning the management and the site-specific matter fluxes arise (Kersebaum et al., 2007). To reduce these uncertainties, usually only a few different prototype crop rotations are considered, which are based on expert-knowledge or designed according to good farming practice (Brisson et al., 2003; Klöcking et al., 2003; Rounsevell et al., 2003; Schönhart et al., 2011). However, the degree to which these assumptions on the occurrence of crop rotations can meet reality is in question. Therefore, the overarching goals of this study are (i) to produce a crop sequence data set for the study area using multiannual crop classifications and (ii) to identify spatio-temporal patterns on the actually practiced crop rotations within the crop sequence data. A central hypothesis within the process of classifying different crop rotations is that the crop sequence data has to include at least eight consecutive years. The latter is due to the fact that crop rotations in central Europe can cover a timespan from two to five years (Castellazzi et al., 2008; Munzert, 2006).

The analysis of satellite remote sensing data is a cost-effective way to generate up-to-date crop classification maps for larger areas at various scales (Atzberger, 2013; Conrad et al., 2010; Thenkabail, 2012; Waldner et al., 2015; Wardlow et al., 2007; Wu et al., 2015). By combining the precise multiannual crop type data, a data base for the spatio-temporal identification of crop sequences and crop rotations can be built. For crop mapping on a regional scale (larger than 1000 km^2), usually multispectral remote sensing data of moderate spatial resolution (ca. 10–30 m) is still the most reasonable choice. Nevertheless, many studies also demonstrate the potential of satellite-borne synthetic aperture radar (SAR) data (Bargiel and Herrmann, 2011; Hütt et al., 2016; Koppe et al., 2013; McNairn et al., 2014) and their combination with optical data (Blaes et al., 2005; Forkuor et al., 2014; McNairn et al., 2009; Lussem et al., 2016) for land use/land cover mapping.

In any case, the generation of comprehensive crop classification maps is usually hampered by limits in the technical capabilities of remote sensing systems (e.g. spectral or radiometric resolution), with regard to high spectral similarities of certain crop types. Varying crop development (e.g. winter/summer crops) or weather conditions (Whitcraft et al., 2015) are additional aspects, which hinder the crop differentiation. These factors necessitate multitemporal observations to capture and differentiate all crop types. Nowadays, the consideration of crop phenology and multitemporal data is well established to achieve results superior to monotemporal classifications (Conrad et al., 2010; De Wit and Clevers, 2004; Foerster et al., 2012; Siachalou et al., 2015; Turker and Arikan, 2005; Waldhoff et al., 2012). For the reduction of misclassifications caused by the confusion with non-agricultural vegetation, ancillary information like topographical data (Bareth, 2001; Rohierse and Bareth, 2004) or agricultural parcel boundary data (Smith and Fuller, 2001) are additionally incorporated using GIS-methods. Such approaches are often enhanced by integrating expert-knowledge in the form of production rule-based methods (Bareth, 2008; Lucas et al., 2011; Roy et al., 2015; Waldner et al., 2015) or via decision trees (Peña-Barragán et al., 2011; Peña et al., 2014). The major advantage of integrating available GIS data sources in remote sensing classifications is the avoidance of classifying urban or non-agricultural vegetation as crop or grassland. Additionally, land use information that cannot be retrieved from remote sensing data, for instance on urban, industrial, mining, or transportation land use, can be integrated in the final land use product. Finally, other studies focus more on multi classifier set-ups (Löw et al., 2015), sophisticated state-of-the-art algorithms like random forest (Belgiu and Drăguţ, 2016; Long et al., 2013) or on the fine-tuning of training data to improve crop mapping results (Mathur and Foody, 2008).

Concerning the general multitemporal crop classification strategy, methods building upon the combined analysis of multitemporal images in a single data stack (Li et al., 2015; Wardlow et al., 2007; Zheng et al., 2015) can be differentiated from a group of various approaches, which combine analysis results of multiple remote sensing datasets in a sequential or nested fashion (De Wit and Clevers, 2004; Turker and Arikan, 2005; Van Niel and McVicar, 2004; Waldhoff et al., 2012). Incidentally, these approaches are applied in a per-pixel as well as in an object-based fashion (Blaschke, 2010). In this regard, Duro et al. (2012) or Dingle Robertson and King (2011) report that in general none of these two fundamental approaches can be considered superior to the other, when using moderate spatial resolution image data.

However, since rather large areas have to be fully covered year by year for regional studies, different framework conditions apply compared to single year studies. As a result, not all approaches may be adequate for the production of uniform crop maps of multiple years, which can be combined to provide crops sequence information at the field level, and to finally conduct crop rotation mapping at the field level. For instance, larger study areas are sometimes not entirely covered by a single remote sensing scene. This may be due to the study area size, offsets between the study area location (and the extent) and the ground pass of the remote sensor swath or, especially in temperate mid-latitude regions, due to cloud coverage (Whitcraft et al., 2015). In such cases, sufficient remote sensing data coverage can only be obtained by additionally incorporating scenes from multiple sensors, which just cover fragments of the study area. As a result, varying spatial and temporal remote sensing image coverage may lead to different preconditions for the crop identification for the individual study area fragments. Furthermore, analysis methods, which are highly adapted to specific input imagery and/or acquisition conditions may not be beneficial, if their adaption to other remote sensing data requires time consuming modifications to the algorithm (Franklin et al., 2011).

In this context, the central task of this study was the design and the application of a robust and annually reproducible crop mapping approach, which can cope with temporally and spatially fragmented remote sensing data. Besides the consideration of crop phenology, the integration of spatially precise data on agricultural land use and land cover from official data sources was a key factor to obtain the desired information. We addressed this by combining remote sensing analysis procedures and GIS-methods for the integration of ancillary information and expert knowledge on crop phenology in a Multi-Data Approach (MDA).

For the generation of a profound data base for crop rotation mapping, this MDA has been used for annual crop type mapping for eight consecutive years (2008–2015). The annual crop mapping methodology and validation of the achieved results is exemplarily illustrated in this contribution for the year 2015. The MDA concept was then extended, to combine the eight annual crop maps to a single dataset to obtain crop sequence information. Finally, with the analysis of the resulting crop sequence dataset we address the overarching question, if crop rotations can be sufficiently identified and can be used as input parameter for regional agro-ecosystem modeling of our study area.

2. Study area and crop phenology

2.1. Study area

The catchment of the river Rur is mainly situated in western Germany (North Rhine-Westphalia, NRW), but it also reaches into the Netherlands and Belgium. To include entire municipalities in Germany, the study area was slightly expanded to about 3400 km^2 in total. The available ancillary data used for the analysis differs between the countries. In this paper, the methods and results for the German part in NRW are presented.

The northern part of the study area is characterized by mainly flat