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Large-area assessment of impervious surface based on integrated analysis of single-date Landsat-7 images and geospatial vector data

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ABSTRACT

Driven by a constantly accelerating increase of urban population in recent decades urban sprawl has become one of the most dynamic processes in the context of global land use transformations. The expansion of urban agglomerations is closely associated with a substantial increase of impervious surface. In Europe, methods for an accurate, fast and cost-effective mapping and assessment of impervious surface on a state-wide or national scale have not been established so far. This study presents an approach for estimating the impervious surface based on a combined analysis of single-date Landsat images and road network and railway vector data using Support Vector Machines and functionalities of geographic information processing. The modeling aims at the provision of data on the impervious surface for the total of residential, industrial and transportation-related areas. The derived information is provided for the administrative units of communities. The output of the procedure is a vector data file providing the 'percent impervious surface of built-up areas' (PIS_B) and the 'percent impervious surface of the total of built-up and transportation-related areas' (PIS_{BT}) for the administrative units of communities. The developed method is tested for a study area covering almost one third of the German territory. The results prove the suitability of the approach for a widely automated and area-wide mapping of impervious surfaces. Using reference data sets of three cities (Leipzig, Ludwigshafen, Passau) we realized a mean absolute error of 19.8% and an average error of 6.4% for the percent impervious surface modeled on the basis of the Landsat images. The final product resulting from a combination of the imperviousness raster derived from the satellite images with the transportation-related vector information showed a mean difference of 1% to 4% compared to corresponding reference data and results of previous studies. For the year 2000 our research shows that 45.3% of the area occupied by settlements and transport infrastructure in the German federal state of Bavaria, 44.6% in the state of Baden-Württemberg and 42.6% in the state of Saxony was covered by impervious surface.

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1. Introduction

The constant loss of land resources due to growing settlements and transport infrastructure is a widespread phenomenon in most developed and emerging countries (Cervero, 2000; EEA, 2006; Lopez & Hynes, 2003). In Germany – for instance – the reallocation of natural and agricultural land to built-up and transportation-related area constantly exceeds 100 ha per day (DESTATIS, 2007). Urban sprawl implies various negative consequences such as the irreversible loss of essential soil functions and excessive runoff during rainfall events (Cieslewicz, 2002; Ewing, 1994; Johnson, 2001; Netzband et al., 2007). Sachs et al. (2000) show that the loss of agricultural land due to urban sprawl predominantly takes place on the most valuable soils. Moreover, the incoming solar radiation is increasingly used for heating rather than evaporation — a fact that intensifies the emergence of urban heat islands (Jones et al., 1990). From an economical perspective the maintenance of the established infrastructure burdens the budgets of the municipalities (Schiller & Siedentop, 2006).

In policy and environmental research, the quantification of impervious surface has become an important indicator for estimating and assessing the negative effects of the ongoing consumption of land resources. Impervious surface (IS) describes the entirety of impermeable surfaces including roads, buildings, parking lots, railroads or other infrastructural elements of urban areas such as squares and sidewalks. In Germany, the systematic assessment of the impervious surface area (ISA) is limited to local surveys by communities and cities that use the information for the calculation of sewer charges. These data are mostly generated by manually digitizing the ISA using very high resolution (VHR) aerial imagery. This time-consuming and cost-

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intensive method restricts periodic updates and regional mappings (Meinel & Hernig, 2006). For regional and national assessments the ISA is currently approximated by means of official statistics on the 'total area of settlements and transport-related infrastructure' (AST) (DESTATIS, 2007). The AST is derived from area-related cadastral land use data which is updated every four years and which includes the categories 'built-up and undeveloped urban area', 'industrial and commercial complexes', 'recreation area', 'traffic area' and 'graveyards'. Official estimations assume that approximately 43% to 50% of the AST is actually covered by IS. However, such estimations represent a substantial generalization of the situation whereas the IS actually shows strong local variations depending on the urban land use type and the geographic region. In order to compensate for this deficiency, Frie & Hensel (2007) proposed to assign a regionally-varying percent impervious surface (PIS) to specific land use categories forming the statistical category of AST. Nevertheless, estimating IS based on statistical data still features the drawback of its incapability to reflect the local and regional distribution of IS since the minimum mapping unit of studies based on the statistical AST is limited to the administrative unit of a community. This dimension is by far too coarse for differentiated applications addressing issues such as biodiversity, ground water systems, water quality or urban climate.

Remote sensing supplies valuable opportunities for an improved detection and characterization of IS since it facilitates a direct and spatially-detailed mapping and analysis of impervious surface materials. In recent years several approaches towards the characterization of IS using earth observation data and digital image analysis have been presented. Most of these studies are based on medium or high-resolution satellite images. Braun & Herold (2004) considered the correlation between the Normalized Difference Vegetation Index (NDVI) and the PIS based on ASTER data for the region of North Rhine-Westphalia, Germany. A comparable study was carried out using Ikonos data of Minnesota (Sawaya et al., 2003). Braun & Herold (2004), Yang et al. (2003) and Sawaya et al. (2003) stressed the necessity of performing a pre-classification to separate IS from open soil and water bodies in order to improve the accuracy of the analyses. Kampouraki et al. (2006) derived the PIS for real estates provided by cadastral data in the city of Cambridge, UK, using information on the NDVI calculated from QuickBird images. Mohapatra & Wu (2008) trained an Ikonos image with color aerial images in an artificial neural network approach to estimate the PIS of Grafton village in Wisconsin. Kuntz (2001) proposed a combined analysis of interferometric data derived from ERS radar imagery and high-resolution optical data in order to determine the ISA per building block in the city of Berlin, Germany. Information on the greenness derived by a tasseled cap transformation of Landsat imagery was successfully correlated with the PIS in the Twin Cities, Minnesota (Bauer et al., 2008). Yang & Liu (2005) introduce a concept for the characterization of urban spatial growth based on an impervious surface index which is calculated on the basis of the brightness and greenness derived by a tasseled cap transformation of Landsat data. Cablk & Minor (2003) applied a principal component analysis along with spatial morphologic operators to Ikonos imagery in order to assess the impervious surface in the urban area of the Lake Tahoe Basin, which straddles the California–

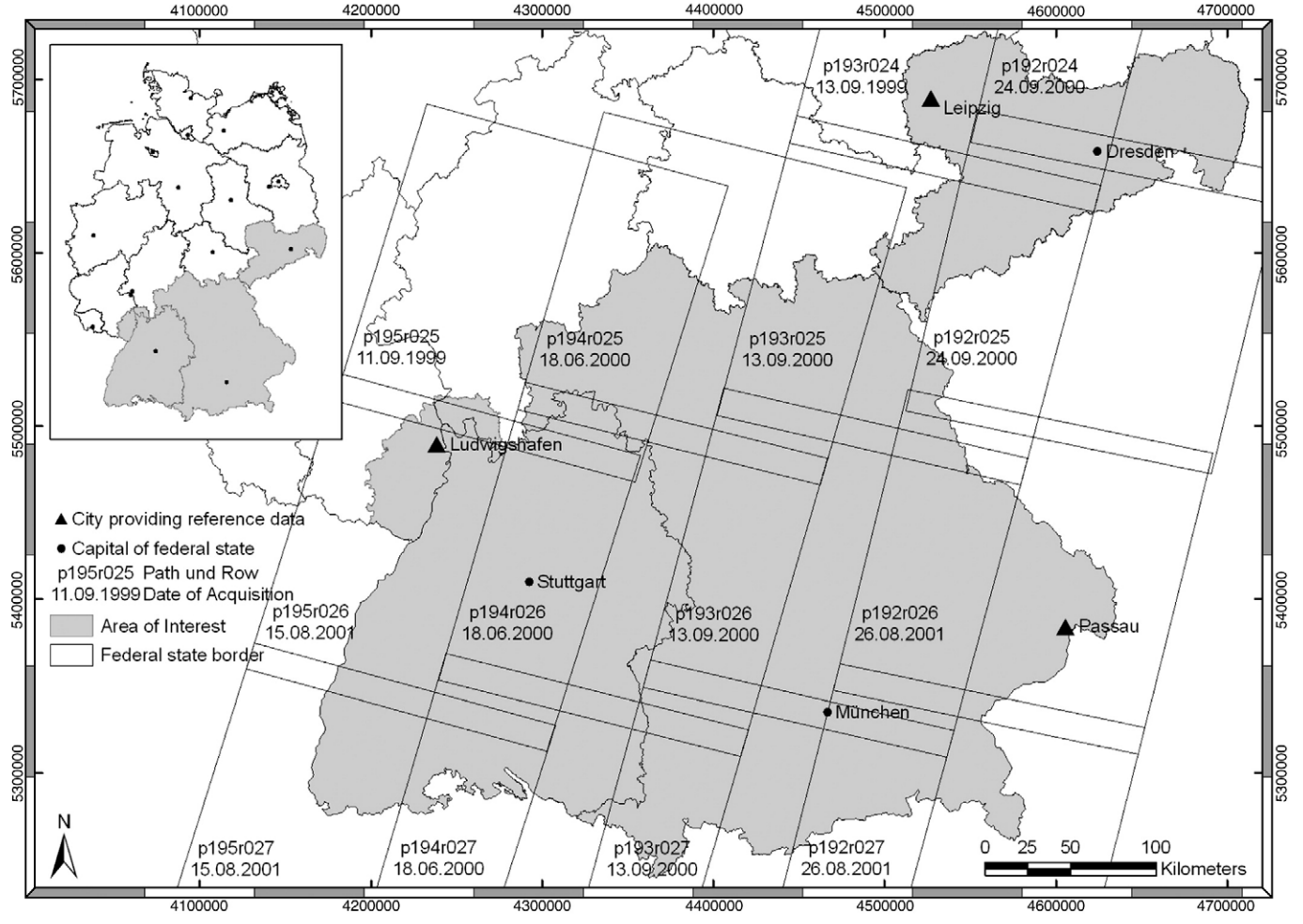

Fig. 1. Overview on the study area overlayed by the Landsat coverage. The triangular symbols mark the location of cities providing reference information for the modeling and accuracy assessment.

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