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Spatio-temporal analysis of agricultural land-use intensity across the Western Siberian grain belt

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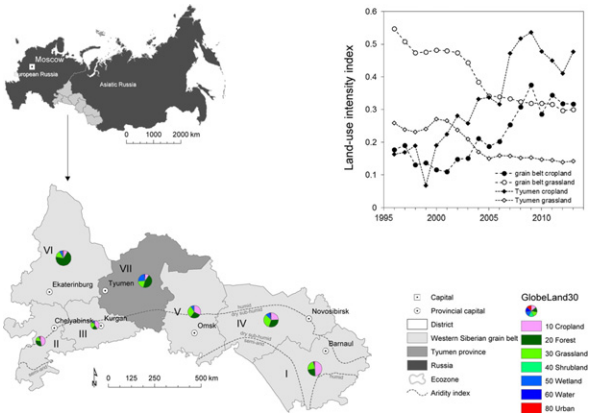
HIGHLIGHTS

- We developed a normalized index to quantify agricultural land-use intensity.
- An individual input-based index was calculated for cropland and grassland.
- Land-use intensity changed significantly across post-Soviet Western Siberia.
- Intensification on cropland and a decrease in intensity on grassland was observed.
- Sustainable land management demands a different strategy for each land-use type.

GRAPHICAL ABSTRACT



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ABSTRACT

The Western Siberian grain belt covers 1 million km² in Asiatic Russia and is of global importance for agriculture. Massive land-use changes took place in that region after the dissolution of the Soviet Union and the collapse of the state farm system. Decreasing land-use intensity (LUI) in post-Soviet Western Siberia was observed on grassland due to declining livestock whilst on cropland trends of land abandonment reversed in the early 2000s. Recultivation of abandoned cropland as well as increasing fertilizer inputs and narrowing crop rotations led to increasing LUI on cropland during the last two decades. Beyond that general trend, no information is available about spatial distribution and magnitude but a crucial precondition for the development of strategies for sustainable land management. To quantify changes and patterns in LUI, we developed an intensity index that reflects the impacts of land-based agricultural production. Based on subnational yearly statistical data, we calculated two separate input-orientated indices for cropland and grassland, respectively. The indices were applied on two spatial scale: at seven provinces covering the Western Siberian grain belt (Altay Kray, Chelyabinsk, Kurgan, Novosibirsk, Omsk, Sverdlovsk and Tyumen) and at all districts of the central province Tyumen. The spatio-temporal analysis clearly showed opposite trends for the two land-use types: decreasing intensity on grassland (−0.015 LUI units per year) and intensification on cropland (+0.014 LUI units per year). Furthermore, a spatial concentration towards intensity centres occurred during transition from a planned to a market economy. A principal component analysis enabled the individual calculations of both land-use types to be combined and revealed a strong link between biophysical conditions and LUI. The findings clearly showed the need for having a different

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strategy for future sustainable land management for grassland (predominantly used by livestock of households) and cropland (predominantly managed by large agricultural enterprises), which have to be addressed specifically by the different land users. As all input data are publicly available, the approach described is readily transferable to other regions or countries of the former Soviet Union.

1. Introduction

To meet the increasing global demand for food and fodder (Godfray et al., 2010), strategies for sustainable management of agricultural land are needed (Foley et al., 2011). The concept of sustainable intensification (The Royal Society, 2009) may help to match the goals of food security for a growing world population under continuous loss of arable land (Foley et al., 2011; Godfray et al., 2010; Smith, 2013; Tilman et al., 2011). Besides the output of agricultural goods, land-based production also affects ecosystem services and functions and biodiversity (Kuemmerle et al., 2013). A crucial precondition for the development of strategies for sustainable intensification is knowledge about the intensity patterns and dynamics of agricultural land use itself (Armengot et al., 2011; Erb et al., 2013; Shriar, 2000).

Many studies focus on land-cover changes, but attempts to describe changes in land-use intensity are scarce, although they are an essential base for further ecological and economic analyses (Erb, 2012). Depending on the production intensity, the effect of land use on ecosystems can largely vary in magnitude and spatial scale, but there is no consensus about how to define or measure this land-use intensity in detail (Dietrich et al., 2012; Erb et al., 2013).

In this paper, we address the agricultural dimension of land-use activities and their impact on the environment, hereinafter referred to as land-use intensity (LUI). LUI can be quantified in different ways (Lambin et al., 2000): some approaches measure agricultural intensity by output (tons, calories, etc.) (Turner and Doolittle, 1978), others are based on inputs (Herzog et al., 2006) or use surrogates like cropping frequency (Temme and Verburg, 2011) and the use of technology (Dietrich et al., 2012; Shriar, 2000; Turner and Doolittle, 1978). Further methods have been described, which integrate more than one dimension of agricultural land-use activity (e.g. Armengot et al., 2011; Blüthgen et al., 2012; Haberl et al., 2007), whereas Erb et al. (2013) explicitly demand a multidimensional approach by considering inputs, outputs and system changes to map LUI in an adequate way. Another, more indirect way for determining LUI is to use or integrate the yield gap approach (Dietrich et al., 2012; Václavík et al., 2013). Besides these differences in methodology, analyses on LUI differ greatly in scale and resolution, depending on the research questions and data sources used, which can vary from surveys over national statistics to satellite imagery (Kuemmerle et al., 2013). To cover the land-based impacts of agricultural production on the (agro-)ecosystem, input-orientated intensity indices are most suitable (Kleijn et al., 2009). In contrast to calculations based on outputs, input-based indices reflect the actual influence on the environment, in particular at low eco-efficiencies of production systems.

The Western Siberian grain belt is part of the Eurasian semi-arid grain belt (Wright et al., 2012), located in the Asian part of the Russian Federation. Most of Russian farmland is located in European Russia, but nearly 30% (22.3 Mha in 2014) are located in Asia (ROSSTAT, 2015). In Siberia, agricultural production predominantly takes place in the southern provinces of the Western Siberian lowland (Chelyabinsk, Sverdlovsk, Kurgan, Tyumen, Omsk, Novosibirsk and Altay Kray). Together they constitute over 70% of the non-European cropland in Russia and more than 20% of all arable land of the Russian Federation since 2000 (ROSSTAT, 2015). Nevertheless, most studies on land use and agriculture focused on European Russia (i.a. Ioffe and Nefedova, 2004; Ioffe et al., 2004; Schierhorn et al., 2013, 2014a). Studies on a global scale often aggregate results as only one value for the entire area of Russia (e.g. Dietrich et al., 2012; Siebert et al., 2010; Václavík et al., 2013), which can hardly reflect the heterogeneity of agricultural production of the world's largest country. Furthermore, many studies on Russian agriculture have focused mainly on the large areas of abandoned land that occurred after 1991 with the collapse of the Soviet state farm system (e.g. Alcantara et al., 2013; Ioffe et al., 2004; Kurganova et al., 2014; Prishchepov et al., 2013; Schierhorn et al., 2013). With different methods, they estimated ratios of cropland abandonment from 23 to 39%. For the neighbouring region of northern Kazakhstan abandonment rates up to 45% are described (Kraemer et al., 2015). In contrast, the development of LUI on the continuously used farmland (cropland and grassland) has rarely been studied, especially beyond Europe. Besides the trend of land abandonment and reclamation in Western Siberia, large-scale changes in management intensity on agricultural land are observed. Moreover, most studies describe only developments of cropland intensity, but agriculture also takes place on grassland with major impacts on LUI since the collapse of the collective farm system. For landscape planning and the development of strategies for a sustainable land management, it is necessary to know the spatial distribution and temporal development of LUI across these two major land-use types.

Here, we present a method for a spatio-temporal assessment of input-based LUI on grassland and cropland separately and apply these indices at two different spatial scales: for seven provinces of the Western Siberian grain belt as well as for 22 districts within the central province Tyumen. In this framework of spatial patterns and time trends in LUI we derive recommendations for sustainable land management strategies.

2. Materials and methods

2.1. Study region

The Western Siberian grain belt is located in the southern part of the Western Siberian plain bordered by the Ural mountains in the west, which divide Russia between Europe and Asia, and the Altai mountains in the east (Fig. 1A). The border with Kazakhstan marks the southern boundary, and to the north, the grain belt is marked-off by closed forests of the taiga ecozone (boreal forest zone). The Western Siberian grain belt stretches across seven provinces, namely Altay Kray (I), Chelyabinsk (II), Kurgan (III), Novosibirsk (IV), Omsk (V), Sverdlovsk (VI) and Tyumen (VII). These provinces cover together 1 million km². Agriculture dominates in the forest steppe zone but is less pronounced within the Pre-Taiga. On average, 27% (range: 9–49%) of the total area are covered by cropland (Fig. 1B), with a considerable concentration in the southern parts of the belt. Grassland covers on average 23% (range: 13–32%) of the area, but there is no spatially discrete information available whether it is used for agricultural purposes or is in a near-natural state. The climate is continental and semi-arid in the south-east and more humid in the north and at higher elevation (CGIAR-CSI, 2009). Mean annual temperatures range from −6.9 °C in the north and towards higher elevations to +4.5 °C in the south-east, and mean annual precipitation ranges from 904 mm to 268 mm (WorldClim, 2013). Due to the short growing season, arable farming is dominated by summer crops, mainly spring wheat. Cropland is predominantly cultivated by large agricultural enterprises, which manage vast areas of up to 50,000 ha (ROSSTAT, 2015). Animal husbandry is mainly characterised by dairy and cattle farming, but also housed livestock