Strategies for sustainable agricultural land use in Western Siberia (Russian Federation)

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PhD Thesis
Osnabrück University
2017

Strategies for sustainable agricultural land use in Western Siberia (Russian Federation)

Dissertation
zur Erlangung des Doktorgrades (Dr. rer. nat.)
des Fachbereichs Kultur- und Sozialwissenschaften
der Universität Osnabrück

vorgelegt
von

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Osnabrück
2017

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Tag der mündlichen Prüfung:

17.05.2017

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List of Abbreviations

a	year
ANOVA	analysis of variance
BK	Biostation Kuchak
BNF	biological nitrogen fixation
CA	conservation agriculture
CT	conventional tillage
EI	ecological intensification
FACE	free air CO_2 enrichment
FAO	Food and Agriculture Organisation
FSU	former Soviet Union
GCM	global circulation model
GER	Germany
GHG	greenhouse gas
GIS	geographic information system
GMO	genetically modified organism
ha	10,000 m^2
LSU	livestock unit
LUI	land-use intensity index
MG	maturity group
NT	no-till
NUE	nitrogen use efficiency
RUS	Russia
RZT	root zone temperature
SI	sustainable intensification
SLM	sustainable land management
SPAD	special products analysis division (chlorophyll meter)
TSW	thousand seed weight (soybeans)
TKW	thousand-kernel weight (cereals)
p	probability level
PCA	principal component analysis
VWC	volumetric water content
WH	Waldhof

Chapter 1

General Introduction

1.1 Background and objectives

The growing global population and the ongoing loss of arable soils lead to an increasing demand for agricultural production (Tilman et al. 2011). In conjunction with climate change, this causes new challenges for agricultural production systems worldwide (Foley et al. 2005; Foley et al. 2011). Agricultural systems of the future need to be shaped sustainably to deal with the changing boundary conditions. Sustainable Land Management (SLM) is known as a synthesis of sustainable development approaches in terms of land use, particularly agricultural land use (Smyth and Dumanski 1993). An international and interdisciplinary working group introduced the SLM idea in 1991 and launched the following definition (Smyth and Dumanski 1995):

"SLM combines technologies, policies and activities aimed at integrating socio-economic principles with environmental concerns so as to simultaneously:

- maintain or enhance production/services (Productivity)
- reduce the level of production risk (Security)
- protect the potential of natural resources and prevent degradation of soil and water quality (Protection)
- be economically viable (Viability)
- and socially acceptable (Acceptability)."

At present, many international and intergovernmental organisations (i.e. FAO, World Bank) are promoting the SLM approach with a strong relation to agriculture.

Project Background

The interdisciplinary German-Russian research project 'SASCHA - Sustainable land management and adaptation strategies to climate change for the Western Siberian grain belt' focused on the interplay and interdependencies of land use, climate change, and the services provided by ecosystems in Tyumen region (SASCHA 2015). The Western Siberian grain belt is not only of global significance for agricultural production but is also an important carbon sink and of international interest for biodiversity preservation. Within the SASCHA project, adaptation strategies to cope with the multidimensional and complex interactions between land use, climate change and population growth were developed to encompass local and regional scales.

Objectives

The objective of this work was to identify strategies for sustainable agricultural land management in Western Siberia on different scales with a focus on arable farming issues. Therefore, the following research questions were addressed:

(1) What does the history of agricultural land use across the Western Siberian grain belt tell us for developing future strategies?

(2) How can the eco-efficiency of Western Siberian cereal cropping systems be increased under the strain of changing climatic conditions?

(3) Is soybean cultivation capable of diversifying crop rotations in the southern part of Western Siberia?

All analyses took place in the interdisciplinary context of the SASCHA project. Hence, the findings reflect perspectives that extend beyond the study of agronomy, taking into account socio-economic considerations and issues of nature conservation.

1.2 Methodology and structure of the thesis

This thesis is arranged according to the cumulative approach: five peer-reviewed papers are compiled after a general introduction and synthesised in the general discussion and conclusion. The analysis of historical land-use schemes to derive a spatio-temporal pattern of land-use intensity in the Western Siberian grain belt was completed based on statistical data collected on the subnational level and conducted through GIS methods (1st paper, chapter 2.1). From these results, scenarios for possible future SLM were developed against a socio-economic background for Tyumen province (2nd paper, chapter 2.2). For the specific sustainable cropland strategies, major approaches were tested in agronomic field trials. The potential of no-till in dryland cropping of Western Siberia was compared to traditional tillage systems on a large-scale split-split-plot field trial conducted with ordinary farming equipment over a two year period on a farmer's field of 11 ha in the southern part of Tyumen province (3rd paper, chapter 2.3). On the same field, the performance of a novel slow-release fertilizer was tested using a randomized complete block design against usual fertilizer strategies for one season on 3.4 ha (4th paper, chapter 2.4). A small-scale trial to evaluate the potential of growing soybeans as new pulses in the high latitude environment of Western Siberia was conducted over two years. This trial was arranged in the same split-plot design as a study from a high latitude German site to allow for comparison between the two study environments (5th paper, chapter 2.5). Combined, the results from all individual studies contribute to the multi-scalar mosaic of sustainable agricultural land use in the Western Siberian grain belt influenced by factors of climate change (**Figure 1**). The first two papers are already published, paper 4 is in press and papers 3 and 5 are currently being reviewed.

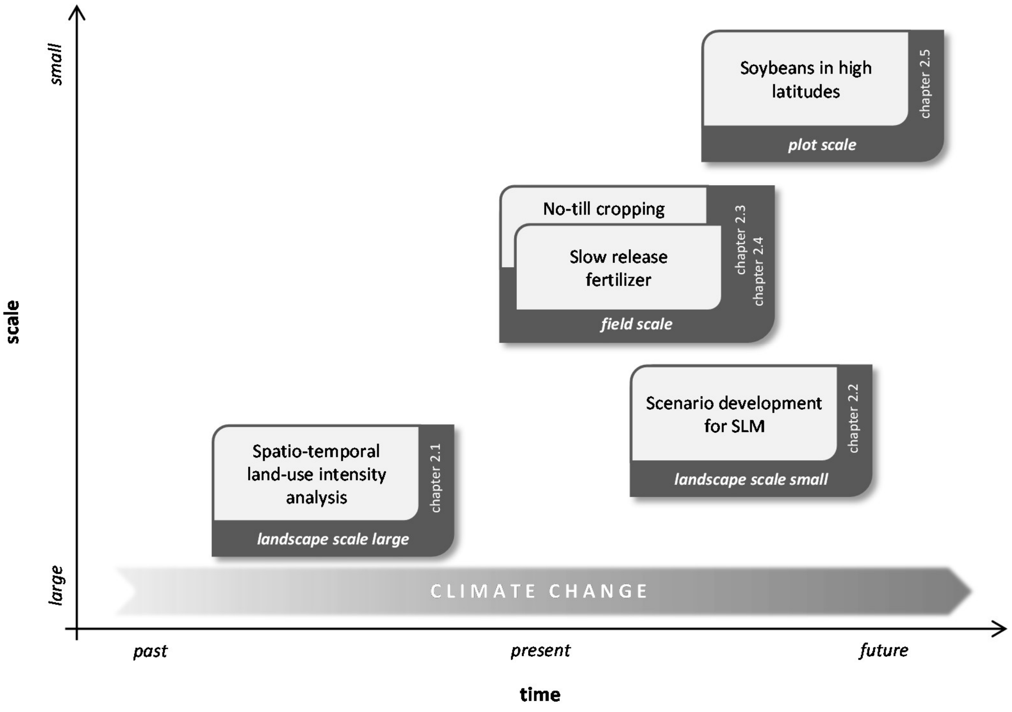


Figure 1: Spatial and temporal positioning of the individual contributions to sustainable land management (SLM) strategies for the Western Siberian grain belt

1.3 The Western Siberian grain belt

1.3.1 Natural environment

The geographic extent of Western Siberia is usually understood as the western part of Asiatic Russia between the Urals and the Yenisei River (Groisman et al. 2013b). The administrative borders of the Russian Federation designate Siberia to a smaller extent as a Federal district of 12 provinces with Novosibirsk as administrative centre. Western Siberia is referred to hereinafter in the wider, geographical meaning. Vast areas of this region belong to the flat topography of the River Ob catchment, designated as the Western Siberian plain or lowlands (Mueller et al. 2015). The Eurasian semi-arid grain belt stretches to the southern part of the Western Siberian plain. The border with Kazakhstan marks the southern boundary of the Western Siberian part of the Eurasian grain belt, and to the north, it is confined by dense forests of the taiga ecozone (**Figure 3**)

The history of settlement in Western Siberia is relatively short. The Russian colonisation began around 1750, when farmers were searching for suitable agricultural land in the south (Groisman et al. 2013b; Mueller et al. 2015). The main driving force behind the emergence and growth of the cities was the building of the Trans-Siberian-Railway that was completed in 1916 (Fedorov 2013). About 70 % of the population live in the major cities that are located in the southern part of Western Siberia, connected to the main railway network (ROSSTAT 2016). Vast areas of the rural landscape are sparsely inhabited. However, there is a strong tradition of urban Siberians to have a dacha (rural second dwellings with a small plot of land) where they grow their own vegetables and fruits.

In addition to large areas of natural habitat, most of the prospected energy resources (oil, gas, coal) of the Russian Federation are also located in Siberia (Groisman et al. 2013b). Therefore, despite Siberia's remote location, it forms the backbone of the Russian economy (Mueller et al. 2015). The human development index as proxy for prosperity of Tyumen region is ranked directly after Moscow and St. Petersburg, listing per capita income in the Ural federal district as the highest (Wegren 2012). This leads to regional reinvestments in the agricultural sector and supports rural development. Furthermore, Mueller et al. (2015) describe Western Siberia as a region of extremes and superlatives with a pronounced prospect of further development within the boundaries of harsh climate and massive stocks of natural resources. This contrast of modern and fast-growing cities and industries developing in close proximity to small settlements, vast agricultural areas, and the native minorities' traditional way of living in the north was also identified by Fedorov (2013) as a strong driver for future development.

1.3.2 Agricultural land use

Nearly one third of the arable farmland in the Russian Federation is located in Siberia. Due to the short growing season in the north, it is mostly concentrated in the southern part within the forest-steppe and steppe zones (Groisman et al. 2013b). The forest-steppe is a 200 km transition zone between forest and steppe (Mueller et al. 2015). The mosaic landscape is characterised by small-scale transitions of pine and birch forest into open grassland and cropland (Selezneva 1973). Steppe covers the southernmost part of the Western Siberian grain belt; a lack of precipitation formed these largely treeless grasslands.

Cropland is located on fertile loess or loess-like sediments at the northern boundary of the Chernozem belt, mainly along the river valleys. Typical soils are leached Chernozems (Phaeozems or Agro-Chernozems following the Russian taxonomy) in the forest steppe. Predominantly Chernozems and dark Kastanozems developed on fine sandy aeolian loess sediments in the steppe (Mueller et al. 2015). Arable fields in the forest steppe are typically large (several hundred ha) but surrounded and interrupted by small remnants of forest, meadows or lakes.

Arable farming in Western Siberia is characterised as typical dryland cropping with a production limit by lack of moisture (Stewart et al. 2006). Short growing seasons and high water balance deficits in summer lead to typical, fallow-based spring cereal rotations (Suleimenov et al. 2010).

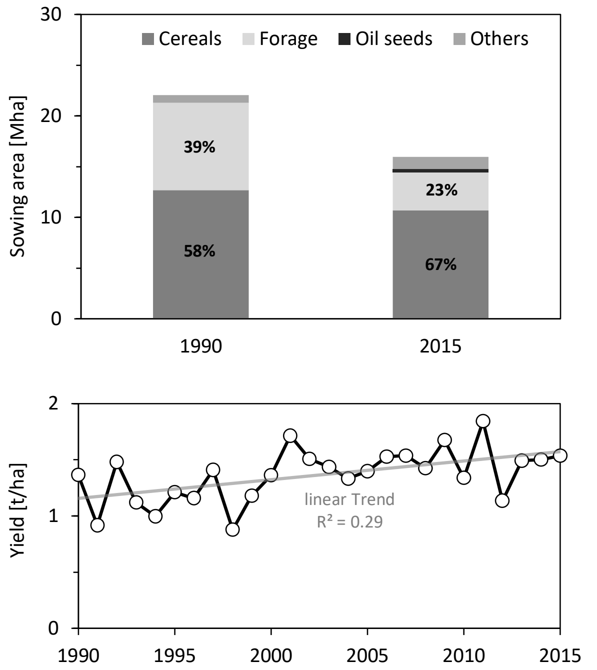


Figure 2: Acreage share of selected crops (top) and cereal yields as average of the 7 provinces of the Western Siberian grain belt (bottom, ROSSTAT 2016).

Along with the aridity gradient, the summer bare fallow is implemented every 4 to 10 years in the Western Siberian grain belt (Suleimenov et al. 2015). In the Kazakh steppe, fallow is practised up to every second year (Wall et al. 2007). Today the dominant crop is spring wheat, followed by other spring cereals (barley, oats), field peas, and increasing areas of oilseed rape. Perennial forage crops have decreased in importance (**Figure 2**, ROSSTAT 2016). The lack of soil moisture is also limiting the effect of mineral fertilizer (Mueller et al. 2015), usually only one application of nitrogen during sowing as band application directly into the seed furrow is practised (▸ see chapter 2.4 for a novel approach of controlled release fertilizer).

During the fallow years, mainly performed by mechanical weed regulation, the bare soil becomes prone to wind erosion (Suleimenov 2006). Since only small areas are under irrigation, most of the cropland is prone to frequent droughts (Groisman et al. 2013b). Conservation agriculture can be implemented to cope with both challenges (▸ see also chapter 1.4.1 and 2.3). Predicted climate change impacts will lead to increasing risks for dryland cropping in Western Siberia. Alcamo et al. (2007) estimated tripled production shortfalls by the year 2070 (▸ see chapter 1.3.4 for climate change).

Most of the grain produced in Western Siberia is consumed within the region, since the distance to the next harbour for grain trading is extremely far (Dronin and Kirilenko 2008). The growing sector of intensive pig and poultry farming demands most of the grains (Mueller et al. 2015). Nevertheless, agricultural intensity is still low across the Western Siberian grain belt compared to Central Europe (Siebert et al. 2010; Dietrich et al. 2012; Levers et al. 2015; Estel et al. 2016). Moreover, Mueller et al. (2015) identified a clear gradient of agricultural intensity according to the distance to urban centres and to the Trans-Siberian railway (▸ for land-use intensity see also chapter 2.1).

Even though the agricultural productivity in Western Siberia is comparatively low, it is due to the large extent of global importance for the world total grain production (Liefert et al. 2010).

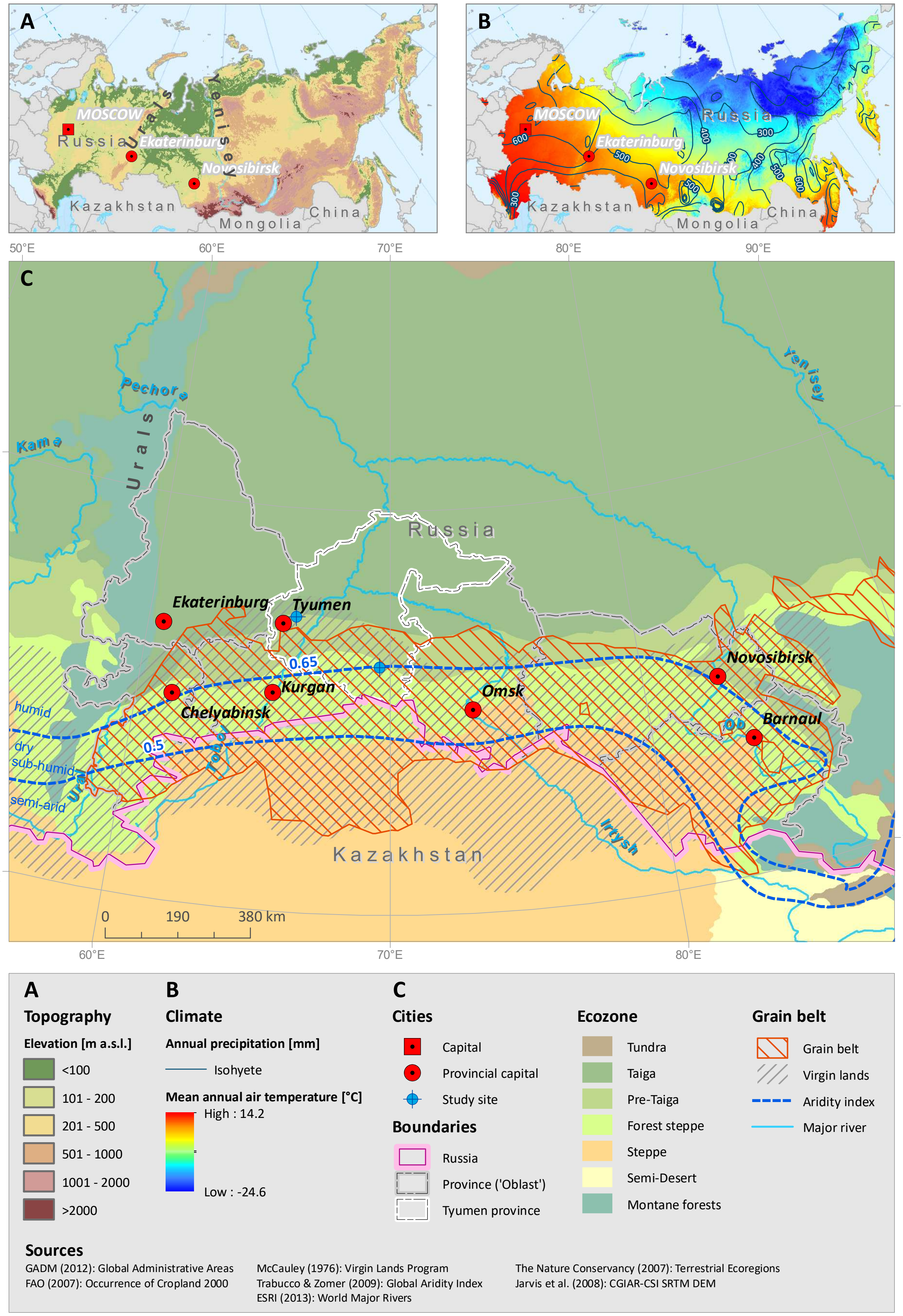
Agriculture in the southern edge of Western Siberia benefits from autonomous regions in the north and their oil and gas industries (Dronin and Kirilenko 2011). Furthermore, the Western Siberian grain belt is not only of global significance in terms of wheat production but also an interesting region for foreign agro-investments (Petrick et al. 2013; ▸ see chapter 2.2 for detailed post-Soviet agricultural structures and their socio-economic implications).

1.3.3 Land-use change

Politically induced land-use change has a long tradition in Siberia. Already in the 18th century people from minority groups like Old Believers were sent to settle in Siberia (Treadgold 2015).

Virgin lands

The first of three periods of the Virgin Lands Campaign occurred from 1928 to 1932 (Durgin 1962). During this period the large-scale ploughing of so-called 'new lands', formerly natural steppe and fallow lands began on nearly 15 million ha (Mha). A second campaign took place from 1940 to 1944 on more than 16 Mha, which accompanied the migration of about 111.000 rural households (Durgin 1962). The main virgin lands campaign was between 1954 and 1960 under the programme of Khrushchev. During this period additional 45 Mha were subsequently converted into cropland, nearly half of it located on Russian territory (Kraemer et al. 2015). Several hundred new settlements have been constructed in the empty steppe to maintain the newly established sovkhozes and kolkhozes (Durgin 1962).



Sources

GADM (2012): Global Administrative Areas
FAO (2007): Occurrence of Cropland 2000
McCauley (1976): Virgin Lands Program
Trabucco & Zomer (2009): Global Aridity Index
ESRI (2013): World Major Rivers
The Nature Conservancy (2007): Terrestrial Ecoregions
Jarvis et al. (2008): CGIAR-CSI SRTM DEM

Figure 3: Map of the Western Siberian grain belt with actual cropland extent and initially cultivated area during the virgin lands campaign. Agro-environmental boundary conditions: world major ecozones and global yearly aridity index (P/ETpot)

During Soviet times, nearly half of the grain was produced on the new lands. The agricultural production during this time followed the plan of the Central Committee of the communist party and, to a significant extent, occurred on marginally productive sites (Lioubimtseva and Henebry 2012).

Abandonment

Another politically induced change in land use was the cropland abandonment after the break-up of the USSR and the collapse of the state farm system in 1991 (Kuemmerle et al. 2011; Horion et al. 2016). The abrupt abandonment of 45 Mha cropland (23 % of the agricultural area) was the most widespread land-use change of the northern hemisphere in the 20th century (Kurganova et al. 2014). Together with a sharp decline in livestock, land-use intensity decreased in the Western Siberian grain belt as well as all in the former Soviet Union as a whole (**Figure 4**). With remote sensing approaches and geo-statistical methods, cropland abandonment mainly for the European part of the former Soviet Union (FSU) was analysed intensively (e.g. Alcantara et al. 2012; Prishchepov et al. 2012b; Sieber et al. 2013; Alcantara et al. 2013; Stefanski et al. 2014). The detailed rates and spatial pattern, however, remained still partly unknown (Kuemmerle et al. 2008). On ex-arable land this led to mostly positive impacts on the environment like carbon sequestration or biodiversity (Kurganova et al. 2014; Kämpf et al. 2016c) whereas on grassland a moderate grazing pressure is preferable over succession (Dengler et al. 2014).

Recultivation

Around the year 2000, recultivation of abandoned cropland occurred (**Figure 5**), mainly on sites with relatively favourable conditions for agricultural production (Prishchepov et al. 2013; Kraemer et al. 2015). More remote areas as well as less suitable soils are still abandoned and have high potential for grassland recovery (Kämpf et al. 2016c). Despite the ongoing recultivation trend, it is unlikely that all of the abandoned cropland will be repurposed for agricultural production, because a considerable share of these soils have limited productivity (Lioubimtseva and Henebry 2012).

Intensification

During the transition from a centralised to market-oriented economy, a tendency of intensification occurred due to the selective recultivation of only sites with better biophysical conditions and the prolonged abandonment of marginally productive areas. Hence, the production level on the cultivated land increased. Due to reforms in the agricultural policy and subsidies, the use of fertilizer and machinery increased (ROSSTAT 2016). In terms of fertilizer application rates, the doubled rate in use since 1999 is only a small fraction of that unnecessarily high amounts that were used during the late 1980s (Lioubimtseva and Henebry 2012). Since farmers have to purchase their mineral fertilizer on the

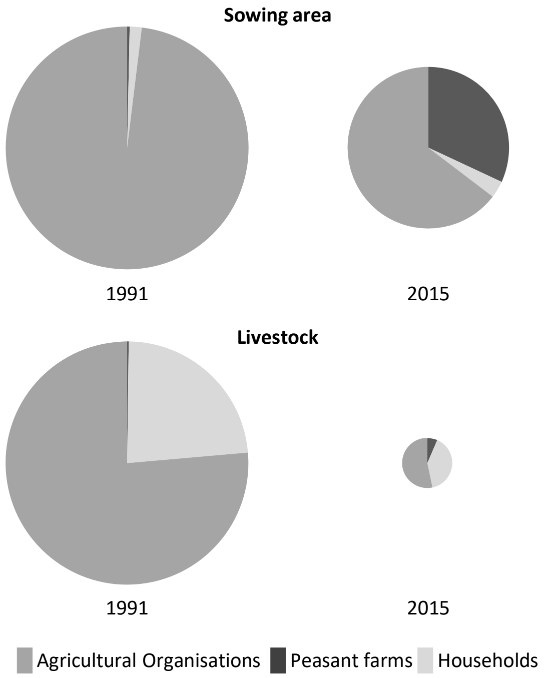


Figure 4: Significant increases in share of peasant farms (cropland management) and household (animal husbandry) since collapse of the Soviet state farm system. Numbers are aggregated for the 7 provinces of the Western Siberian grain belt (ROSSTAT 2016), standardised livestock units weighted after EUROSTAT (2014). Pie size for 1991 was set up to 100 %.

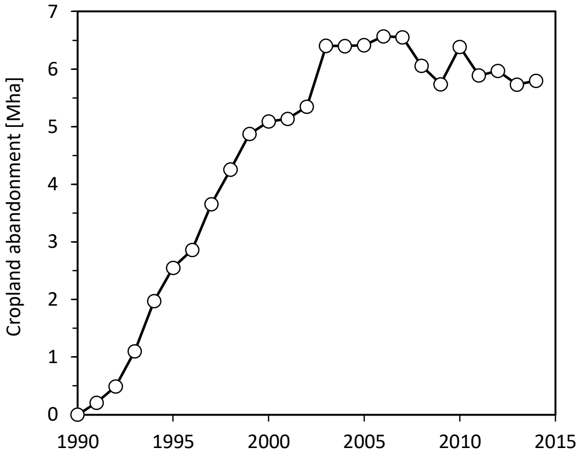


Figure 5: Area of abandoned cropland after the dissolution of the Soviet Union within the Western Siberian grain belt summed up for the 7 provinces (ROSSTAT 2016)

market now, the transition has led to increased eco-efficiency in comparison with the more heavily regulated economy of the past (Liefert and Liefert 2012) (▸ see chapter 1.4.1 for eco-efficiency and sustainable intensification).

Recently, changes in intensity on agricultural land are more pronounced than change from one land-use type to another, with various impacts on the agro-ecosystem. The significant and ongoing intensification on cropland needs to be shaped in a sustainable way whereas the decreasing intensity on grassland is likely to cause biodiversity losses (▸ see chapter 2.1 and 2.2).

1.3.4 Climate change

Global warming will affect agriculture worldwide, but in varying levels of intensity depending on geographic location. In general, agriculture in the northern hemisphere is likely to benefit from climate change and agriculture in global south will probably suffer the brunt of the impacts (Rosenzweig and Parry 1994; Cline 2007; Wheeler and Braun 2013). In the northern high latitudes, particularly Russia, Canada and China are probably going to benefit in terms of agricultural production (Fischer et al. 2005; Zabel et al. 2014). All over northern Eurasia there is a strong climate change signal (IPCC 2013) but the changes in Western Siberia are described by e.g. Pilifosova et al. (1997) and Groisman and Soja (2009) to be among the largest and most quickly accelerating. Moreover, the large extent and the significant carbon storage in peat soils of Western Siberia underline the significance of this region for global climate feedback potential (Kremenetski et al. 2003; Frey and Smith 2003).

Past observations

During the past century, the climate of Siberia became much warmer and except of an increase of cold season precipitation (snow) north of 55° N, no change in precipitation occurred (Groisman et al. 2013a). In conjunction with relatively constant boundary conditions like soil type, soil organic matter, groundwater level etc., this led to drier growing conditions. These conditions persists particularly during the summer season with increased frequency of drought and fire. The detailed analysis of the past observations in the south of Western Siberia by Degefie et al. (2014) confirmed a significant upward trend in temperature related indices and growing season length but no significant change in precipitation related indices. From an agro-environmental point of view, some changes in pests and diseases developed as a result. For example, locusts and the Colorado beetle (*Leptinotarsa decemlineata*) became more active in the late 20th century in Western Siberia (ROSHYDROMET 2008).

Future predictions

Based on the past observations, a large set of global circulation models (GCM) is available to predict future climate changes following different scenarios (IPCC 2013). All of these global predictions agree about substantial changes with implications for plant growth. Modified biophysical conditions will lead to reshaping of ecosystems in Western Siberia (Brédoire et al. 2016). Altered seasonal energy and water budgets will trigger a northward shift and variation in the size of major ecozones in Northern Eurasia, particularly Siberia (Soja et al. 2007; Tchebakova et al. 2009; Groisman and Soja 2009). The area currently occupied by forest steppe and steppe is likely to increase (Kicklighter et al. 2014).

Regional downscaling of GCM provides more detailed information about the future climate conditions across the Western Siberian grain belt. The temperature increases are going to be more pronounced in the cold season than in the warm season and will foster longer growing seasons (Groisman et al. 2013a; Degefie et al. 2014). Dronin and Kirilenko (2011) estimated a possible shift of of suitable agricultural areas up to 600 km to the north. Within the current extent of agriculture, cultivation of new species will be possible due to a shift of their northernmost distribution boundary (Kicklighter et al. 2014). Nevertheless, the lower soil fertility outside the Chernozem belt will limit the expansion of agriculture into the boreal forest zone (Dronin and Kirilenko 2011).

Consequences for agriculture

Climate change affects several strong interacting factors with different feedback for agricultural production. Growing seasons lengthened by increasing temperatures may allow to grow crops with higher temperature requirements. On the other hand, it may lead to emergency ripening if the water storage is emptied too early in the season. Many regional studies report an increasing frequency of extreme events, but not all of them have been proofed for statistical significance. However, it is difficult to draw a conclusion of all impacts, since most results are based on models which can hardly be validated for future predictions.

Alcamo et al. (2007) indicated that besides the climate change induced increase of the agricultural potential, Western Siberia would also face new problems like drought stress. Limits in production increase under changing water regimes are also related to longer wet periods in spring (Dronin and Kirilenko 2011). The risk of more frequent droughts by rising temperatures, in particular during spring and summer together with no significant changes in precipitation was also reported by Kiselev et al. (2013) and Degefie et al. (2014). This change in the water balance will furthermore expand the area of soils that are prone to salinity (Chernousenko et al. 2011). In addition to changes in abiotic factors, further global warming will promote an increasing risk of pests and diseases in Western Siberia's crop production, where the pressure recently is very low (ROSHYDROMET 2008).

Yield estimations under climate change predictions vary in a wide range depending on the used models or scenarios. Kicklighter et al. (2014) revealed a possible increase in food production by 15 % in Northern Eurasia. Sommer et al. (2013) estimated an average increase in wheat yields by 12 % from northern Kazakhstan. Alcamo et al. (2007) found short time positive yield responses of 10-54 % but negative effects in the long run. Sirotenko et al. (1997) predicted increased productivity in Russian agriculture up to 60-70 % if the production systems will be well-adapted to the new conditions (redistribution of cropping areas, new technologies) but negative consequences with a business as usual scenario. Further assessments in economic values describe advantageous situations for agricultural production under changing climate in Russia (Fischer et al. 2005). Lioubimtseva and Henebry (2012) reported benefits of several hundred billion US$ by increased grain production of 1.5-2 times in Russia due to the expansion of agricultural zones to the north. On the contrary ROSHYDROMET (2008) assumed a decrease in cereal crop productivity by 10-20 %. Even more pessimistic reported Pavlova et al. (2014) 20-40 % yield decrease due to water shortfalls from a single model approach for spring wheat yields in the steppe zone.

Not all of the above-mentioned studies and models reflected changes in CO_2 concentration. In general, there is consensus about the positive fertilization effect of elevated CO_2 concentrations in the atmosphere for primary productivity of C3 plants (White et al. 2011). In particular, under water limited conditions, the positive yield feedback is pronounced due to a better water use efficiency by decreased stomatal conductance (Reich et al. 2014). Legume species, especially soybeans, are known to profit above average among the C3 plants (Parry et al. 2004). Recently published results, mainly from free air CO_2 enrichment (FACE) experiments, reveal opposite effects in field trials. Fitzgerald et al. (2016) observed significantly higher yields (+70 %) under elevated CO_2 conditions in semi-arid Australia for wheat. Alternatively, Gray et al. (2016) could not confirm the advantages of higher CO_2 concentration for soybeans under drought stress within an 8-year experimental timespan. There is a gap between spatial predictions from modelling and point results from FACE experiments. The overall tendency for the Western Siberian grain belt is still an ongoing debate.

Taking all positive and negative aspects into account, Dronin and Kirilenko (2011) concluded overall, climate change is having a negative impact on agriculture in Russia. Pilifosova et al. (1997) modelled negative agro-environmental consequences with regional downscaling of GCMs for northern Kazakhstan, which is transferable for the southern edge of the Western Siberian grain belt. In contrast, Lioubimtseva and Henebry (2012) concluded a positive net benefit for Russia, Ukraine and Kazakhstan from longer vegetation periods, uncertain precipitation changes and increased CO_2 concentrations. In their estimation, the area with agro-ecological constraints will shrink and the area for profitable dryland cropping will expand. All described changes, however, will affect agricultural production in future and sustainable cropping systems need to be adapted to the new conditions (▸ see chapter 1.4.1 and 2.3).

1.4 Concepts of sustainable agricultural land management

1.4.1 Sustainable Intensification

Agricultural systems of the future need to be more productive, stable, and resilient while minimising environmental impacts (Tilman et al. 2011). Within the SLM community, a new concept for agricultural land management emerged in 2009, where The Royal Society launched their report "Reaping the Benefits". Since then, the concept of 'Sustainable Intensification' (SI) has been discussed frequently in high-level publications (e.g. Foley et al., 2011; Garnett et al., 2013; Godfray et al., 2010; Tilman et al., 2011). Moreover, SI has become a central element in the strategy of both the FAO and the Consultative Group on International Agriculture Research (CGIAR).

The fundamentals of SI are defined by The Royal Society (2009) as follows:

(1) utilise crop varieties and livestock breeds with a high ratio of productivity for externally and internally derived inputs;
(2) avoid the unnecessary use of external inputs;
(3) harness agro-ecological processes such as nutrient cycling, biological nitrogen fixation, allelopathy, predation and parasitism;
(4) minimise use of technologies or practices that have adverse impacts on the environment and human health;
(5) make productive use of human capital in the form of knowledge and capacity to adapt and innovate and of social capital to resolve common landscape scale or system wide problems;
(6) minimise the impacts of system management on externalities such as greenhouse gas (GHG) emissions, clean water, carbon sequestration, biodiversity, and dispersal of pests, pathogens and weeds.

It can be concluded, that the need for increased production should be met through higher yields rather than by expanding cropland area (Garnett et al. 2013). However, these key elements describe rather a goal for future agricultural management than providing a prescription for particular agricultural techniques.

Sustainability & ecosystem services

The word origin of sustainability reaches back to balanced timber management in 17th century, but since the Brundtland report 'Our Common Future' in 1987 it has been understood in a more human dimension (UN 1987). Sustainability encompasses three pillars: ecological, economic, and social concerns. Furthermore, it considers intra- and intergenerational justice and intends to implement this from local to global scale. In conjunction with agriculture, sustainability is less sharply characterised, but often agricultural practices that maintain ecosystem services are mentioned in sustainable context. Ecosystem services are defined as the benefits that humans get from ecosystems (MEA 2005). Usually the term distinguishes between supporting services (i.e. nutrient cycling, soil formation), regulating services (i.e. pest control, pollination, climate regulation), provisioning services (i.e. food, fossil energy, water) and cultural services (i.e. recreation, aesthetics).

Agricultural intensification

Agricultural intensification of the past made marked increases in yields possible by a combination of breeding progress, mechanisation and the increased use of mineral fertilizers and agrochemicals. After switching from industrialised countries into the tropics it came to be known as the 'Green Revolution'. Indicators for intensification are a doubled area under irrigation, 7-fold consumption of nitrogen fertilizers and application of 2.5 billion kg a^{-1} of synthetic pesticides during the 20th century (Pretty and Bharucha 2014). This had a remarkable environmental impact and made agricultural systems less efficient. Nevertheless, some experts are still proposing a targeted use of fertilizers to close yield gaps (Tilman et al. 2011; Mueller et al. 2012) and in 2008, the FAO stated, that no technology should be excluded (Tittonell 2014). That includes the use of genetically modified organisms (GMO) as one possible pathway of intensification.

Ecological Intensification

During the last few years, a new term appeared with increasing frequency in the discourse about SI:

'Ecological Intensification' (EI). Bommarco et al. (2013) described EI as a management of ecosystem services within cropping systems by the environmentally friendly replacement of anthropogenic inputs through enhanced regulating and supporting services. Caron et al. (2014) described enhanced performances by intensifying of ecological processes and functionalities in cultivation procedures as EI. Tittonell (2014) identified the main difference between SI and EI as the role nature plays in the design of the systems, and the possible synergies between food security and global change: SI and eco-efficiency approaches are targeting on a single farm whereas EI needs to involve the complexity of the landscape.

Eco-efficiency

Another expression that is often mentioned in the context of SI and EI is 'eco-efficiency'. Whilst ordinary efficiency is defined as the ratio between output and input, the concept of eco-efficiency views the output term as a function of positive and negative components (Eq. 1). Eco-efficiency as a measure of the economic value added over the environmental pressure generated is therefore a possibility of measuring progress towards SI (Gadanakis et al. 2015). In the context of agriculture, this could mean that a given input in terms of nitrogen fertilizer leads to a positive output of a certain grain yield but simultaneously results in an undesirable output of nitrogen load into the aquatic ecosystem. Eco-efficiency is therefore related to both, ecology and economy (Lal 2010) or in can be seen as trade-off between them (Gadanakis et al. 2015).

$$Efficiency_{eco} = \frac{Output_{eco}}{Input} \quad \text{with} \quad Output_{eco} = f\,(pos, neg) \quad (1)$$

SI aims at increasing eco-efficiency in agricultural production and there are several pathways to do so. Beyond the simple efficiency enhancement by producing more with the same input, eco-efficiency is also increased if the same positive output can be produced with less negative output (Eq. 2).

$$Efficiency_{eco}\uparrow = \frac{Output_{pos}\uparrow, Output_{neg}\leftrightarrow}{Input\leftrightarrow}$$

or

$$= \frac{Output_{pos}\leftrightarrow, Output_{neg}\downarrow}{Input\leftrightarrow} \qquad (2)$$

The negative external effects of agricultural production on the environment are manifold: short-term impacts like water pollution or soil compaction as well as consequences in the long run, like biodiversity loss and climate change. A sustainable approach to feeding the growing global population involves an increased focus on increased eco-efficiencies instead of production maximisation. In particular, the time dimension of sustainability requires the responsible handling of the agro-ecosystem resources, otherwise no next generation need to produce food. To cope with the upcoming challenges not only does agricultural production need to be sustainably intensified, but re-distribution of food on the global scale, dietary shifts in the developed world and a reduction of food waste will be required (Loos et al. 2014).

Implementation

The scientific community agrees about the necessity of SI in agriculture, nevertheless this apparent simple approach is hardly transferable into agricultural practice. Since the launch of the report by The Royal Society (2009) some 1000 highly-rated papers were released, dealing with SI on different scales but mostly on a theoretic 'meta-level' as "a vaguely defined global vision" (Loos et al. 2014). This is due, in part, to the fact that SI remains an umbrella term that includes many different practices and technologies whereas the precise extent of the existing SI is difficult to estimate (Pretty and Bharucha 2014). Further concerns about definition of SI are the possibility of very different interpretations (Petersen and Snapp 2015). The organic farming movement has expressed much criticism for the contradiction of the two words themselves and the missing crop-livestock integration (Kühling and Trautz 2015a). The under-representation of the social pillar is often criticised and Loos et al. (2014) request a more holistic assessment of SI against the background of global food security.

Practices that are often mentioned as examples for SI are conservation agriculture, integrated pest management, agro-forestry systems, urban agriculture, or management-intensive rotational grazing systems. Organic agriculture is the most popular case-study of EI.

1.4.2 Conservation Agriculture

Agricultural methods of the future will have to produce more food on less land by more efficient use of natural resources and with minimal impact on the environment. Conservation Agriculture (CA) is a modern agricultural practice that can enable farmers all over the world to achieve these goals of sustainable intensification (Lal et al. 2007; Hobbs et al. 2008). CA is defined after FAO (2015) as an "approach to managing agro-ecosystems for improved and sustained productivity, increased profits and food security while preserving and enhancing the resource base and the environment". Three strongly linked principles characterise CA, namely:

(1) Continuous minimum mechanical soil disturbance
(2) Permanent organic soil cover
(3) Diversification of crop species grown in sequences and/or associations (FAO 2015).

This means, that CA is much more than conservational tillage. Tillage systems with minimum soil disturbance cover primarily no-till (NT), sometimes referred to as zero-tillage or direct seeding/direct drilling. Minimum tillage, reduced tillage or systems excepting either temporal (tillage before one crop within the rotation) or spatial (strip-till: tillage in a narrow area beneath the seeds) may also be classified as CA. Those mainly NT-based systems are known to help land users to develop new and improved strategies for SLM through an integrated management of available soil, water and biological resources combined with external inputs (Hobbs et al. 2008). CA, therefore, contributes to environmental conservation as well as to food security in a resource efficient way. The term 'conservation' was mainly intended to describe more careful soil handling but also led to wide acceptance as a concept for a low-intensity, biodiversity-enhancing and climate-smart agricultural system (Pretty and Bharucha 2014; Giller et al. 2015).

After a 7-10 year transition period from conventional (ploughing) tillage, CA leads to improved soil conditions with reduced wind erosion and surface runoff (Derpsch et al. 2014). Soil water storage capacity and infiltration rates are enhanced in CA and therefore minimise drought stress in crop production (Palm et al. 2014). Further improved ecosystem services are biological soil activity and water quality, since more water percolates through the soil filter before recharging the groundwater layer or entering the stream flow (Kassam et al. 2009). The direction of soil carbon stocks is not so clear cut. In the long run there seems to be a re-distribution into the top-most layer more strongly visible than an accumulation over the total profile (Lal 2004; Kämpf et al. 2016b). The same with GHG emissions and soil borne pests – depending on the soil type and the agro-climatic zone top-ranking papers report opposite results. On the one hand Palm et al. (2014) concluded, that CA has a significantly lower global warming potential than conventional tillage systems, by changes in soil carbon alone. On the other hand Powlson et al. (2014) damped the potential of carbon sequestration by NT and highlighted the very limited possibility of climate change mitigation through CA. Their paper was mainly a reaction to 'The Emissions Gap Report', launched by the United Nations Environment Programme in 2013. In a later response, the authors of the UN report emphasise the importance of small holder farming in their assessment, where data is sometimes less precise (Neufeldt et al. 2015). Under climate change, however, positive feedback of CA is likely, particularly for the global north (Pittelkow et al. 2014).

Advantages that are more practice-oriented are reduced time between harvest and sowing, which in turn influences labour cost savings as well as reduced fuel and machinery costs, since tillage is the largest effort in crop production (Kassam et al. 2009). Compared to agriculture that is based on conventional tillage or monocultures, CA is more resilient against extreme events and therefore ensures stable yields. CA always provides better eco-efficiencies and under some agro-ecological conditions is able to provide higher yields.

However, CA usually requires higher amounts of herbicides to control the weeds that are normally regulated by tillage (Hobbs et al. 2008). Still, successful examples of NT in organic farming, where diversified crop rotations are obvious, persist (Gadermaier et al. 2011; Vakali et al. 2011). Nevertheless, CA is primarily practised conventionally, based on the use of mineral fertilizers and agrochemicals.

CA was originally developed as response to the U.S. Dust Bowl, a severe soil erosion that devastated the U.S. Midwest in the 1930s (Baveye et al. 2011). Since then CA spread rapidly across the Americas and Australia (Palm et al. 2014; Giller et al. 2015). Currently, CA is practised all around the world across a wide range of agro-ecological conditions and on various scales but primarily on large-scale, mechanised farms (Hobbs et al. 2008; Pretty and Bharucha 2014). Estimations of about 155 Mha cultivated in CA systems with an annual increase by some 6 Mha globally were reported by Kassam et al. (2014). Jat et al. (2013) further stated large differences between regions: more than 50 % of the cropland is managed with CA in Australia, New Zealand and South America, about 15 % in North America and only about 1 % in Africa and Europe. Unfortunately there are no reliable numbers available for Russia (Derpsch and Friedrich 2009; Derpsch et al. 2010). Theoretically speaking, it is possible to practice CA everywhere, but it needs to be locally adapted (Farooq et al. 2011; Kienzler et al. 2012; Tittonell et al. 2012). Serraj and Siddique (2012) suggest a more active farmer participatory approach especially in smallholder farming. Nevertheless, there is much criticism of the transferability of a system that was developed for high-intensity, mechanised farming with sophisticated machinery, potent agrochemicals and biotechnology to household plots in developing countries (Palm et al. 2014; Giller et al. 2015).

Giller et al. (2015) ascribed the rapid expansion of NT as key component of CA during the 1980-90s as a combination of four factors:

(1) effective herbicides were made more widely available since their release in the 1960s (atrazine, glyphosate);
(2) modern no-till seeders were able to deal with residue mulch;
(3) policy incentives supported the transition in the USA;
(4) the release of genetically modified (GM) crops that are resistant to post-emergence herbicides.

The latter factor particularly promoted the practice of CA on large farms in Australia, Brazil and North America. Together with the increased use of herbicides and cultivation of GM crops – often in continuous cropping – the weeds developed a resistance to herbicides. Since the first report on herbicide resistance in 1970, tolerances in 200 weed species have been identified with an acceleration simultaneous to the cultivation of GM varieties (Farooq et al. 2011). In particular, the repeated use of glyphosate on glyphosate-resistant GM crops lead to a widespread weed tolerance against this and became the major threat for CA worldwide.

Besides these herbicide related adaptations of weed species, tillage induced changes in weed communities accompany NT. Reduced tillage is known to shift the species from annual dicots to grassy annuals and perennials (Nichols et al. 2015). Altered soil properties like higher moisture content and mulch cover lower temperatures and delay weed emergence. Small-seeded annuals in particular will suffer from the shadow of the surface residues. Diverse crop rotations can underline the general competiveness of CA against weeds, most significant with varied sowing dates (spring vs. autumn crops) (Nichols et al. 2015).

Since water conservation is a key function of CA, there is high potential for implementation in dryland areas exposed to erratic and unreliable rainfall, which cover more than 2 million km^2 worldwide (Koohafkan and Steward 2008). To sustain regional and global food production, a lot of policy development aimed at promoting NT in dryland cropping is taking place (Kuhn et al. 2016). Compared to traditional, fallow-based dryland cropping systems that often run wheat monocultures, the new NT crop rotations without fallow years provide various benefits. Better soil moisture accumulation, reduced soil losses through wind and water erosion and better soil fertility management result in a more ecological and economical land use after changing to CA in dryland regions (Suleimenov et al. 2015).

From global meta-analyses, paired field trials conclude, that NT enables higher yields in semi-arid environments, especially for cereal crops (Pittelkow et al. 2015). A regional meta-study from dryland cropping trials in the Chinese Loess Plateau by Kuhn et al. (2016) confirmed these advantages of NT and highlighted that global approaches underestimate the high potential of NT in semi-arid environments. The advantage of NT in dryland cropping systems is even more pronounced if it is implemented within the complete CA system (Farooq et al. 2011; Pittelkow et al. 2014). Long term positive experiences with CA suggest, that it should become the dominant practice in cereal cropping systems of steppe regions, not only in the Americas but also in Eurasia (Suleimenov et al. 2015)

Chapter 2

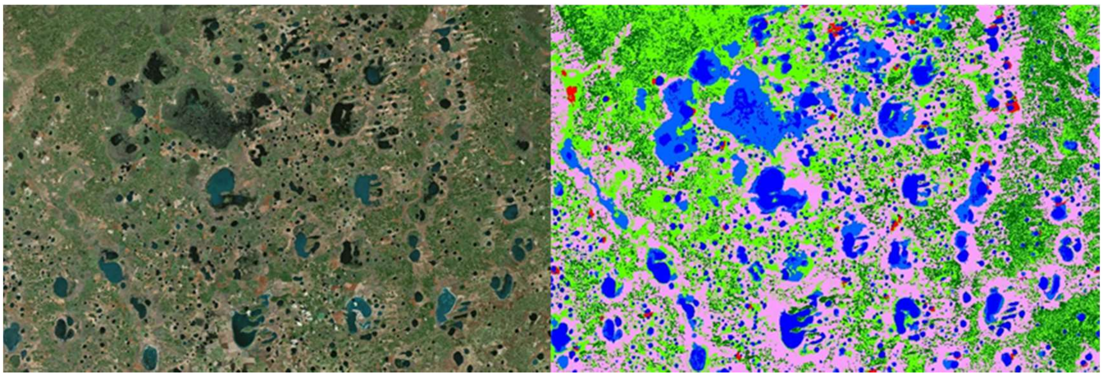
Towards Sustainable Land Management on Different Scales

PICTURE CREDIT

ESRI (2015) & GlobeLand30 (NGCC 2014)
Satellite image and land cover in Tyumen region

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

[Sci Tot Env 544 (2016) 271-280]



AUTHOR CONTRIBUTIONS

Insa Kühling developed the land-use intensity index, performed the spatio-temporal analysis and statistics and wrote the manuscript
Gabriele Broll supervised Insa Kühling
Dieter Trautz supervised Insa Kühling

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Science of the Total Environment 544 (2016) 271-280

SPATIO-TEMPORAL ANALYSIS OF AGRICULTURAL LAND-USE INTENSITY ACROSS THE WESTERN SIBERIAN GRAIN BELT

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Submitted
21 August 2015
Accepted
24 November 2015

Keywords
intensity index
land-use change
post-Soviet
sustainable land management
sustainable intensification, Russia

DOI: 10.1016/j.scitotenv.2015.11.129

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 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.

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 (Godfray et al. 2010; Foley et al. 2011; Tilman et al. 2011; Smith 2013). 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 (Shriar 2000; Armengot et al. 2011; Erb et al. 2013).

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 (Turner and Doolittle 1978; Shriar 2000; Dietrich et al. 2012). 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 et al., 2004; Ioffe and Nefedova, 2004; Schierhorn et al., 2014, 2013). 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.

MATERIALS AND METHODS

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 (Trabucco and Zomer 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 production of pig and poultry is present. Land-based animal husbandry on natural grasslands is performed by low-intensity collective grazing and hay production for winter feeding of livestock based in village households. Larger cattle farms produce their fodder from sown forage cultures on cropland and feed their cattle in stables all year round. In contrast to regular moderate applications of

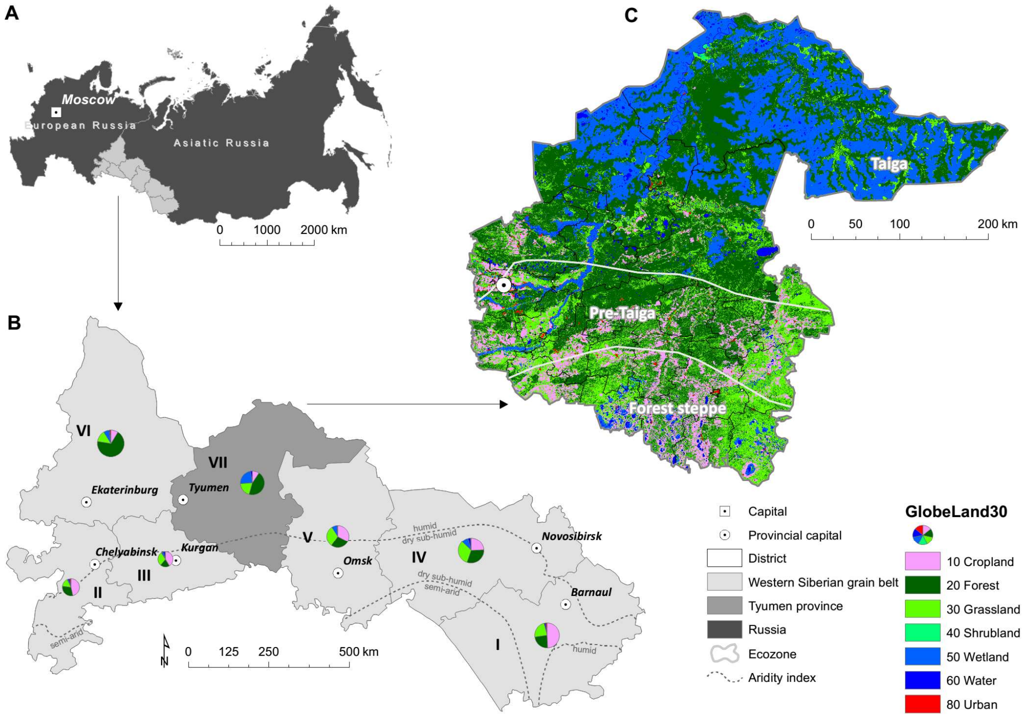

Figure 1: Location of provinces forming the Western Siberian grain belt in the Asian part of Russia (A). Proportion of land use type in each province (B). Spatial distribution of land use types and biomes for the central province Tyumen (C). Roman numbers of provinces according to Table 3. Data sources: Trabucco and Zomer (2009), GADM (2012), NGCC (2014), ROSREESTR (2014).

mineral and partly organic fertilizers on cropland, application of fertilizer is unusual on grassland.

In this paper, we distinguish between these two land-use regimes: (1) grassland both in a natural state and used as pasture or meadow (at maximum mown once a year) and (2) cropland with frequent tillage impact and fertilizer input, used for grain production as well as for sown forage crops.

The large-scale landscape of the Western Siberian plain is characterised by high groundwater levels and high seasonal variability between summer drought and snowmelt (Selezneva 1973). Soil conditions change markedly despite only small changes in topography. Arable farming takes place on large fields (several 100 ha) on fertile soils (predominantly Chernozems, Phaeozems; Selezneva (1973), which are found at higher elevation flat areas between rivers and poorly drained plateaus within a mosaic of birch forest and depressions with lakes, peatlands and grasslands. Areas at low elevation close to the river valleys and drainless depressions are covered with grassland and are not suitable for arable farming due to poor drainage and/or late soil drying in spring. Grazing and episodic mowing is typical for these areas.

Within the central province Tyumen the same gradients and patterns as typical for the entire grain belt occur (Fig. 1C). The 22 districts have a homogeneous, but poor infrastructure network of paved roads and are connected to the Trans-Siberian Railway in the south (ROSREESTR 2014). Every district has its regional capital in a centred position and a central grain storage, mostly with railway connection. The rural landscape is sparsely inhabited with 6.2 people per km² except for the provincial capital vicinities, which have a higher population density of 185.1 persons per km² (TYUMSTAT 2014).

Land-use intensity index

Following Erb et al. (2013), we developed a LUI based on more than one parameter, but restricted to input-based information. As we were interested in effects of land-based agricultural production on the environment, we chose a combination of input variables known as key indicators for agricultural land-use intensity (Herzog et al. 2006; Kleijn et al. 2009). Other effects like e.g. urbanisation or industrial impacts are not covered by this analysis. Because agricultural management is completely different on cropland and grassland, an individual index for each land-use type was calculated, similar to Temme and Verburg (2011) or Blüthgen et al. (2012). As input factors on cropland, we used the total amount of fertilizer (sum of nutrients from organic and mineral fertilizer), the proportion of sowing area and the proportion of sown grain crops. The latter parameter was used because the substitution of perennial forage crops by annual grain crops leads to shorter crop rotations and a higher frequency of tillage operations, which indicates higher LUI (Shriar 2000). For grassland, we aggregated cattle, sheep, goats and horses to grazing livestock units, weighted after EUROSTAT (2014). As cattle from large agricultural enterprises are rarely grazed, only livestock kept by households were considered. The input data were downloaded from www.fedstat.ru and www.tumstat.gks.ru. These governmental data sources have been reported to be reliable in the area of agriculture (Schierhorn et al. 2013). Spatial distribution and area shares of land-use types were derived from a 30m resolution global land cover map from 2010 (www.globeland30.com). Table 1 summarises all sources and the units of the used parameters.

The yearly LUI index was standardized for each land-use type by ranging the individual values of the data matrix between 0 (min) and 1 (max) on both spatial scale (district/province): first by subtracting the minimum observed for each variable and then dividing by the range (Legendre and Legendre 1998).

Cropland (*c*) intensity for every year i (1996–2013) was calculated as the product of total fertilizer input (*Fert*), the proportion of cropland per province/district area (*Pcrop*) and the proportion of grain crops on cropland (*Pgrain*) (Eq. 1)

$$LUIc_i = \frac{c_i - c_{min}}{c_{max} - c_{min}} \quad \text{with} \quad c = Fert * Pcrop * Pgrain \qquad (1)$$

Grassland (*g*) intensity for every year i (1996–2013) was calculated as the product of grazing livestock density (*gLSD*), the proportion of grassland per province/district area (*Pgrass*) and the proportion of grazing livestock units kept by households (*Psubsist*) (Eq. 2)

$$LUIg_i = \frac{g_i - g_{min}}{g_{max} - g_{min}} \quad \text{with} \quad g = gLSD * Pgrass * Psubsist \quad (2)$$

In a second step, the annual LUI values of each land-use type were arithmetically averaged over three time periods of six years to reduce the yearly variability (T1: 1996-2001, T2: 2002-2007, T3: 2008-2013).

Table 1: Parameters (with data sources) used to delineate the annual LUI index on different scales

Parameter			Province level		District level	
Name	**Description**	**Unit**	**Source**	**Year(s)**	**Source**	**Year(s)**
Fert	Total fertilizer input	kg ha^{-1}	ROSSTAT (2015)	1996-2013	TYUMSTAT (2014)	1996-2013
Pcrop	Proportion of cropland in total area of district/province	%	ROSSTAT (2015)	1996-2013	TYUMSTAT (2014)	1996-2013
Pgrain	Proportion of grain crops on cropland	%	ROSSTAT (2015)	1996-2013	TYUMSTAT (2014)	1996-2013
gLSD	Grazing livestock density; aggregated livestock units (LSU) of cattle, sheep/goats and horses on grassland*	LSU ha^{-1}	ROSSTAT (2015) GlobeLand30 NGCC (2014)	1996-2013 2010	TYUMSTAT (2014) GlobeLand30 NGCC (2014)	1996-2013 2010
Pgras	Proportion of grassland in total area of district/province	%	GlobeLand30 NGCC (2014)	2010	GlobeLand30 NGCC (2014)	2010
Psubsist	Proportion of grazing livestock kept in households	%	ROSSTAT (2015)	1996-2013	TYUMSTAT (2014)	1996-2013
area boundaries	Administrative borders	-	GADM (2012)	2012	ROSREESTR (2014)	2014

*weighting factor 1: dairy cows, 0.8: horses, 0.7: beef cattle, 0.1: sheep/goats

Table 2: Description and data sources of environmental and infrastructure variables used for vector fitting onto the ordination diagram of the principal component analysis.

Parameter	Description	Unit	Year(s)	Source	Dataset
temp	mean annual temperature	°C	1950-2010	WorldClim (2013)	raster bio1
prec	mean annual precipitation	mm a^{-1}	1950-2010	WorldClim (2013)	raster bio12
lat	latitude	°	2013	GIS	-
dist_capital	distance to Tyumen	km	2013	GIS calculation	-
dist_railway	distance to nearest railway	km	2002	IIASA and RAS (2002)	line rail_arc
dist_road	distance to nearest road	km	2002	IIASA and RAS (2002)	line road_arc
pop_density	population density	people km^{-2}	2013	TYUMSTAT (2014)	table
soil_arable	area share of soils suitable for arable farming	%	1992 2010	RosGeoCart (1992) NGCC (2014)	vectorised soil type raster GlobeLand30
boundaries	administrative borders	-	2014	ROSREESTR (2014)	vector districts

Statistical analysis

For analysis of the temporal LUI trends, slopes of the LUI time series were calculated for all districts/provinces by linear regression. A two-tailed t-test was used to test Pearson correlations for significance. For Tyumen province, we conducted a principal component analysis (PCA) including the district’s mean LUI values of the three time periods T1, T2 and T3 for cropland and grassland with post-hoc vector fitting of external environmental and infrastructure parameters onto the ordination diagram. The sources of the used variables are listed in Table 2. All distances were computed as Euclidian distances in each raster cell. To get the percentage of arable soils we classified soil types for potential of agricultural cultivation. For further analysis, we calculated mean values within district boundaries of all fitting parameters. The significances of the fitted environmental and infrastructural vectors were tested by 1000 random permutations. All statistical analyses were conducted in R version 3.0.1 (R Core Team 2013). For the PCA we used the R package vegan (Oksanen et al. 2015).

RESULTS

Land abandonment

The trend of land abandonment in the Western Siberian grain belt started to reverse in Tyumen and Kurgan province in 2003, followed by the other provinces in the years until 2010 (ROSSTAT 2015). On average over all provinces, the maximum of cropland abandonment was reached in 2007, when only 67 % of the formerly used arable fields were cultivated. Compared to the extent of sowing area in 1990 before the collapse of the Soviet state farm system, 69 % of formerly abandoned cropland are again under cultivation (Table 3, Fig. 2A).

In Tyumen province, recultivation of abandoned land started early, after the smallest area of crop production of 59 % (2003) compared to the maximal extent since 1990 (ROSSTAT 2015). Until 2013, across Tyumen province 160,000 ha of abandoned land were converted into cropland.

In 2013, an ongoing decrease in grazing livestock numbers had reached a level of only 32 % of the population in 1990 for the Western Siberian grain belt as well as for Tyumen province (Fig. 2A, Table 3).

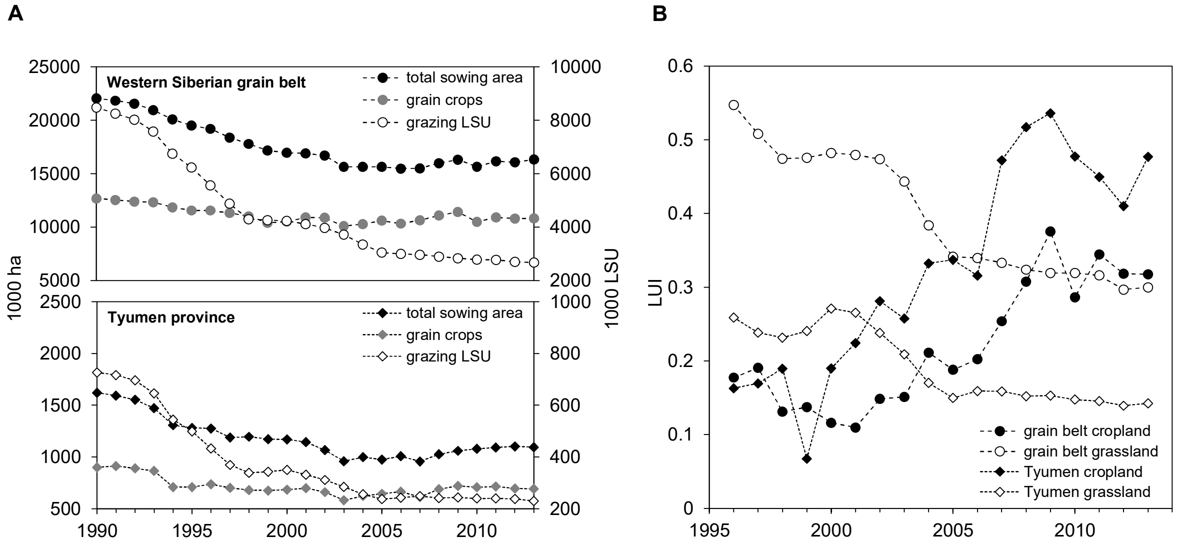

Figure 2: Time series of total sowing area, area sown with grain crops and grazing livestock units (LSU) for the Western Siberian grain belt and Tyumen province (A) and time series of the land-use intensity (LUI) index on cropland and grassland at both spatial scale (B). Source (A): ROSSTAT (2015).

Table 3: Land-use indicators sowing area and grazing livestock numbers as percentage of maximal extent in 1990. ‘LSU’: livestock units. Source: ROSSTAT (2015)

		Sowing area [1000 ha]				**Grazing livestock [1000 LSU]**			
No	**Region Province (kray/oblast)**	**Reference 1990**	**T1: ’96–’01**	**T2: ’02–’07**	**T3: ’08–’13**	**Reference 1990**	**T1: ’96–’01**	**T2: ’02–’07**	**T3: ’08–’13**
	Russian Federation	117705	77 %	66 %	65 %	54011	52 %	41 %	37 %
	W. Siberian grain belt	22053	79 %	68 %	69 %	8482	53 %	38 %	32 %
I	Altayskiy kray	6380	85 %	81 %	85 %	1922	53 %	39 %	32 %
II	Chelyabinskaya oblast	2694	80 %	69 %	75 %	1098	49 %	35 %	32 %
III	Kurganskaya oblast	2640	70 %	47 %	53 %	925	57 %	46 %	42 %
IV	Novosibirskaya oblast	3443	80 %	74 %	70 %	1505	46 %	26 %	21 %
V	Omskaya oblast	3745	84 %	78 %	77 %	1497	57 %	45 %	33 %
VI	Sverdlovskaya oblast	1516	80 %	65 %	57 %	738	50 %	35 %	28 %
VII	Tyumenskaya oblast	1634	73 %	61 %	67 %	796	60 %	43 %	32 %

Spatial patterns of LUI

The calculated current land-use intensity (T3) on cropland ranged between 0.13 and 0.86 (Table 4), with a weighted average of 0.33 for the Western Siberian grain belt. Compared to the early values (T1) the LUI on cropland increased by a factor of 2.3 between 1996 and 2013. The aggregated LUI on province level was related neither to the agro-climatic suitability for crop production nor to the cropland extension (Fig. 3A, 1B). Tyumen province had an above-average LUI on cropland (Fig. 3A), considering the geographical location up to high latitudes and low proportion of forest-steppe.

On grassland, current land-use intensity (T3) ranged from 0.01 to 0.58, the weighted average over all provinces was 0.31 (Table 4). In contrast to the observed intensification trends on cropland, LUI had been reduced 37% on grassland, starting from an initial average LUI of 0.49 in T1. Analogue to cropland intensity, no clear spatial patterns were explainable by special suitability for animal husbandry, as LUI was not correlated with grassland proportion (Fig. 3B, 1B).

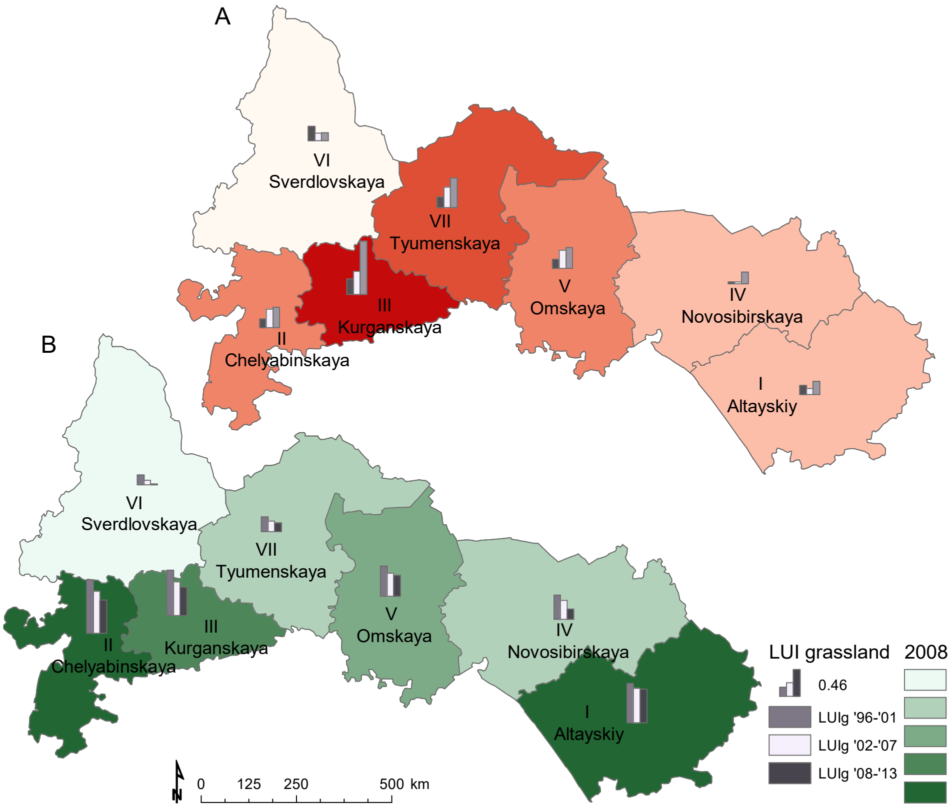

Figure 3: Spatio-temporal LUI map for cropland (A) and grassland (B) in seven provinces of the Western Siberian grain belt.

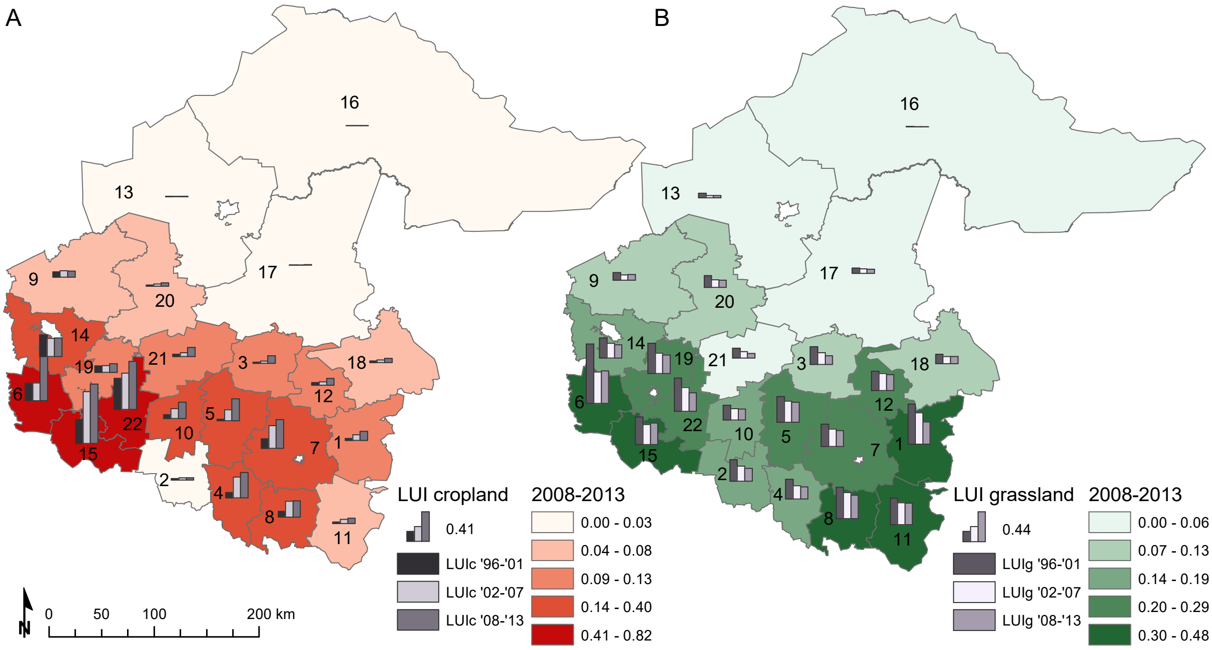

Figure 4: Spatio-temporal LUI map for cropland (A) and grassland (B) in the 22 districts of Tyumen province. Cities are excluded (white shading); numbers of districts according to Table 4; bar plots in the northern districts no. 13, 16 and 17 are close to zero.

Comparing both land-use types, land-use characteristics were fundamentally opposed with exception of Sverdlovsk (VI) and Kurgan (III) provinces: whereas generally lower grassland intensity and higher cropland intensity were observed, in Kurgan province both land-use types were under intensive use. Sverdlovsk province can be considered as an outlier, because of overall low agricultural activities due to high latitudes and elevations, respectively (Table 4, Fig. 3).

In Tyumen province, the LUI for both land-use types showed a clear north-south gradient, as there is nearly no agricultural activity in the three northern districts, which are located within the taiga ecozone (Fig. 4, Table 4). The southern part of Tyumen was characterised by two regions with higher intensity: on the border to Kurgan province in the south-west (districts no. 6, 15, 22) followed by the surrounding of Ishim (district no. 7). In this region, intensity indices were considerably above average on both cropland (0.64 to 0.82) and grassland (0.27 to 0.32), similar to Kurgan province. On the contrary, higher intensity on cropland was located west of Ishim city (districts no. 4, 5, 7), whilst grassland intensity was pronounced to the east (districts no. 1, 8, 11) and vice versa, following the general opposite pattern as described for the entire grain belt.

Temporal trends of LUI

The temporal changes of LUI were significant in both land-use types, but in opposite directions on province as well as on district level (Table 5, Fig. 2B).

On the province scale, LUI on cropland in the Western Siberian grain belt increased on average by 0.014 units per year. The only exception of this highly significant trend was Sverdlovsk (province no. VII), where there was no cropland intensification. The provinces with the highest current LUI (T3) on cropland – Kurgan (no. III) and Tyumen (no. VII) – also experienced the fastest increase over time. Across the entire grain belt, correlations between cropland LUI in T3 and the related slope was positive (0.95 with $R^2=0.91$, $p<0.001$). On grassland a uniform and highly significant negative LUI trend by -0.015 units per year was observed. Differences among provinces were less pronounced than in cropland LUI and the slope was slightly negatively correlated with the former LUI in T1 (-0.68 with $R^2=0.46$, $p<0.001$). Together with the temporal trend of intensification on cropland, also increasing productivity on cropland was observed. Starting from a very low level in the early 1990s, grain yields increased steadily by 22 % on average (Table 6), even in those times when sowing areas declined (Table 3).

On district level within Tyumen province there were identical relations between high current LUI values (T3) and steep slopes for cropland as described for the province scale (Table 5). Again, districts located close to the Kurgan border (no. 6, 15, 22) were prominent and characterised by cropland intensity increasing most rapidly. The steady states of districts no. 13, 16 and 17 were negligible, due to nearly no arable farming in the north. Despite some heterogeneity, correlations between LUI in T3 and an increase over time on cropland were strongly positive (0.89 with $R^2=0.79$, $p<0.001$). Uniformly declining intensity on grassland in the districts of Tyumen was clearly negative correlated (-0.92 with $R^2=0.85$, $p<0.001$) with the earlier (T1) land-use intensity levels.

Drivers of land-use intensity

A principal component analysis (PCA) of LUI for all time periods (T1-T3) on both land-use types revealed a strong link between biophysical conditions and land-use intensity (Fig. 5). The first two principal components together explained 95.97 % of the total variance in the dataset. Where the orthogonal projections of a district's location in the ordination diagram on the LUI vector are close to the tip of the vector, the district has a high land-use intensity. By using this biplot rule, groups of current intensity could be identified by drawing the zero lines for each land-use type, which run perpendicular to the T3-LUI vectors through the origin. Using the intersections of cropland and grassland zero lines, four areas of intensity could be derived: (1) high cropland intensity, (2) high grassland intensity, (3) high intensity at both land-use types and (4) low intensity at both land-use types. These groups correspond with environmental and infrastructure parameters. Districts with high intensity on both land-use types were located under favourable agricultural production conditions (high annual mean temperature; high proportion of soils that are suitable for arable farming). In contrast, over all low intensity was correlated with poor infrastructure (long distances to roads, railway and provincial capital) and unfavourable climatic conditions (high latitudes, high annual precipitation and low mean temperature).

Table 4: Average LUI on cropland and grassland in seven provinces and 22 districts of Tyumen for three periods of six years (T1, T2, T3).

No	Province (‘kray/oblast’) District (‘rayon’)	Cropland			Grassland		
		T1 ’96–’01	**T2 ’02–’07**	**T3 ’08–’13**	**T1 ’96–’01**	**T2 ’02–’07**	**T3 ’08–’13**
	W. Siberian grain belt*	0.14	0.19	0.33	0.49	0.39	0.31
I	Altayskiy kray	0.15	0.10	0.22	0.68	0.59	0.58
II	Chelyabinskaya oblast	0.14	0.30	0.33	0.92	0.72	0.57
III	Kurganskaya oblast	0.25	0.37	0.86	0.78	0.58	0.49
IV	Novosibirskaya oblast	0.03	0.03	0.19	0.42	0.33	0.18
V	Omskaya oblast	0.14	0.29	0.33	0.52	0.40	0.36
VI	Sverdlovskaya oblast	0.23	0.12	0.13	0.17	0.08	0.01
VII	Tyumenskaya oblast	0.17	0.33	0.48	0.25	0.18	0.15
1	Abatskiy rayon	0.03	0.08	0.12	0.59	0.46	0.33
2	Armizonskiy rayon	0.02	0.03	0.03	0.32	0.22	0.19
3	Aromashevskiy rayon	0.02	0.03	0.10	0.26	0.17	0.13
4	Berdyuzhskiy rayon	0.08	0.29	0.35	0.30	0.20	0.18
5	Golyshmanovskiy rayon	0.02	0.15	0.31	0.37	0.31	0.29
6	Isetskiy rayon	0.24	0.25	0.64	0.88	0.46	0.48
7	Ishimskiy rayon	0.13	0.32	0.40	0.33	0.26	0.23
8	Kazanskiy rayon	0.08	0.22	0.23	0.46	0.38	0.34
9	Nizhnetavdinskiy rayon	0.07	0.09	0.08	0.11	0.08	0.08
10	Omutinskiy rayon	0.05	0.13	0.23	0.22	0.16	0.16
11	Sladkovskiy rayon	0.02	0.06	0.07	0.39	0.33	0.32
12	Sorokinskiy rayon	0.03	0.05	0.09	0.28	0.25	0.23
13	Tobolskiy rayon	0.01	0.00	0.01	0.07	0.04	0.03
14	Tyumenskiy rayon	0.30	0.25	0.26	0.29	0.22	0.19
15	Uporovskiy rayon	0.33	0.72	0.82	0.41	0.30	0.32
16	Uvatskiy rayon	0.00	0.00	0.00	0.01	0.00	0.00
17	Vagayskiy rayon	0.00	0.00	0.01	0.08	0.07	0.06
18	Vikulovskiy rayon	0.02	0.04	0.06	0.14	0.11	0.11
19	Yalutorovskiy rayon	0.09	0.09	0.12	0.45	0.30	0.27
20	Yarkovskiy rayon	0.01	0.03	0.04	0.17	0.11	0.11
21	Yurginskiy rayon	0.03	0.05	0.13	0.14	0.09	0.06
22	Zavodoukovskiy rayon	0.43	0.50	0.66	0.49	0.35	0.27

* weighted average by provincial cropland/grassland share of the entire grain belt

Table 5: Slope of LUI time series for 18 years (1996-2013) for each province and Tyumen’s districts.

No	Province (‘kray/oblast’) District (‘rayon’)	Cropland			Grassland		
		LUIc slope	**R^2**	**p**	**LUIg slope**	**R^2**	**p**
	W. Siberian grain belt	0.014	**0.71**	<0.001	-0.015	**0.91**	<0.001
I	Altayskiy kray	0.006	*0.24*	0.041	-0.008	**0.60**	<0.001
II	Chelyabinskaya oblast	0.012	*0.31*	0.016	-0.030	**0.93**	<0.001
III	Kurganskaya oblast	0.045	**0.73**	<0.001	-0.025	**0.90**	<0.001
IV	Novosibirskaya oblast	0.012	**0.61**	<0.001	-0.019	**0.94**	<0.001
V	Omskaya oblast	0.015	**0.52**	<0.001	-0.013	**0.80**	<0.001
VI	Sverdlovskaya oblast	-0.009	**0.60**	<0.001	-0.013	**0.92**	<0.001
VII	Tyumenskaya oblast	0.024	**0.81**	<0.001	-0.008	**0.80**	<0.001
1	Abatskiy rayon	0.008	**0.79**	<0.001	-0.022	**0.94**	<0.001
2	Armizonskiy rayon	0.001	0.16	0.097	-0.010	**0.83**	<0.001
3	Aromashevskiy rayon	0.006	**0.58**	<0.001	-0.011	**0.86**	<0.001
4	Berdyuzhskiy rayon	0.021	**0.70**	<0.001	-0.010	**0.79**	<0.001
5	Golyshmanovskiy rayon	0.023	**0.75**	<0.001	-0.007	**0.57**	<0.001
6	Isetskiy rayon	0.028	*0.49*	0.001	-0.032	**0.67**	<0.001
7	Ishimskiy rayon	0.020	**0.78**	<0.001	-0.008	**0.76**	<0.001
8	Kazanskiy rayon	0.011	*0.50*	0.001	-0.010	**0.81**	<0.001
9	Nizhnetavdinskiy rayon	0.000	0.00	0.937	-0.002	*0.42*	0.004
10	Omutinskiy rayon	0.013	**0.57**	<0.001	-0.005	**0.61**	<0.001
11	Sladkovskiy rayon	0.003	*0.49*	0.001	-0.006	*0.45*	0.002
12	Sorokinskiy rayon	0.005	**0.66**	<0.001	-0.004	**0.76**	<0.001
13	Tobolskiy rayon	0.000	0.00	0.978	-0.003	**0.80**	<0.001
14	Tyumenskiy rayon	-0.003	0.10	0.197	-0.008	**0.86**	<0.001
15	Uporovskiy rayon	0.038	**0.67**	<0.001	-0.008	*0.44*	0.003
16	Uvatskiy rayon	0.000	*0.42*	0.003	0.000	**0.93**	<0.001
17	Vagayskiy rayon	0.000	**0.69**	<0.001	-0.002	**0.82**	<0.001
18	Vikulovskiy rayon	0.003	*0.42*	0.003	-0.003	**0.64**	<0.001
19	Yalutorovskiy rayon	0.002	*0.17*	0.090	-0.014	**0.82**	<0.001
20	Yarkovskiy rayon	0.003	**0.54**	<0.001	-0.005	**0.73**	<0.001
21	Yurginskiy rayon	0.008	**0.72**	<0.001	-0.007	**0.92**	<0.001
22	Zavodoukovskiy rayon	0.018	*0.31*	0.017	-0.018	**0.90**	<0.001

bold numbers: highly significant, italic numbers: significant

Table 6: Regional differences in grain yields in t ha^{-1}. Source: ROSSTAT (2015)

No	Region	Reference '90–'95	T1: '96–'01	T2: '02–'07	T3: '08–'13	Difference T3 over Reference
	Russian Federation	1.57	1.43	1.99	2.13	35 %
I	Altayskiy kray	1.00	0.93	1.13	1.22	22 %
II	Chelyabinskaya oblast	1.12	1.04	1.28	1.08	-4 %
III	Kurganskaya oblast	1.04	1.23	1.42	1.40	34 %
IV	Novosibirskaya oblast	1.23	1.30	1.39	1.50	22 %
V	Omskaya oblast	1.19	1.28	1.40	1.43	20 %
VI	Sverdlovskaya oblast	1.34	1.42	1.54	1.71	28 %
VII	Tyumenskaya oblast	1.57	1.79	2.04	2.06	31 %

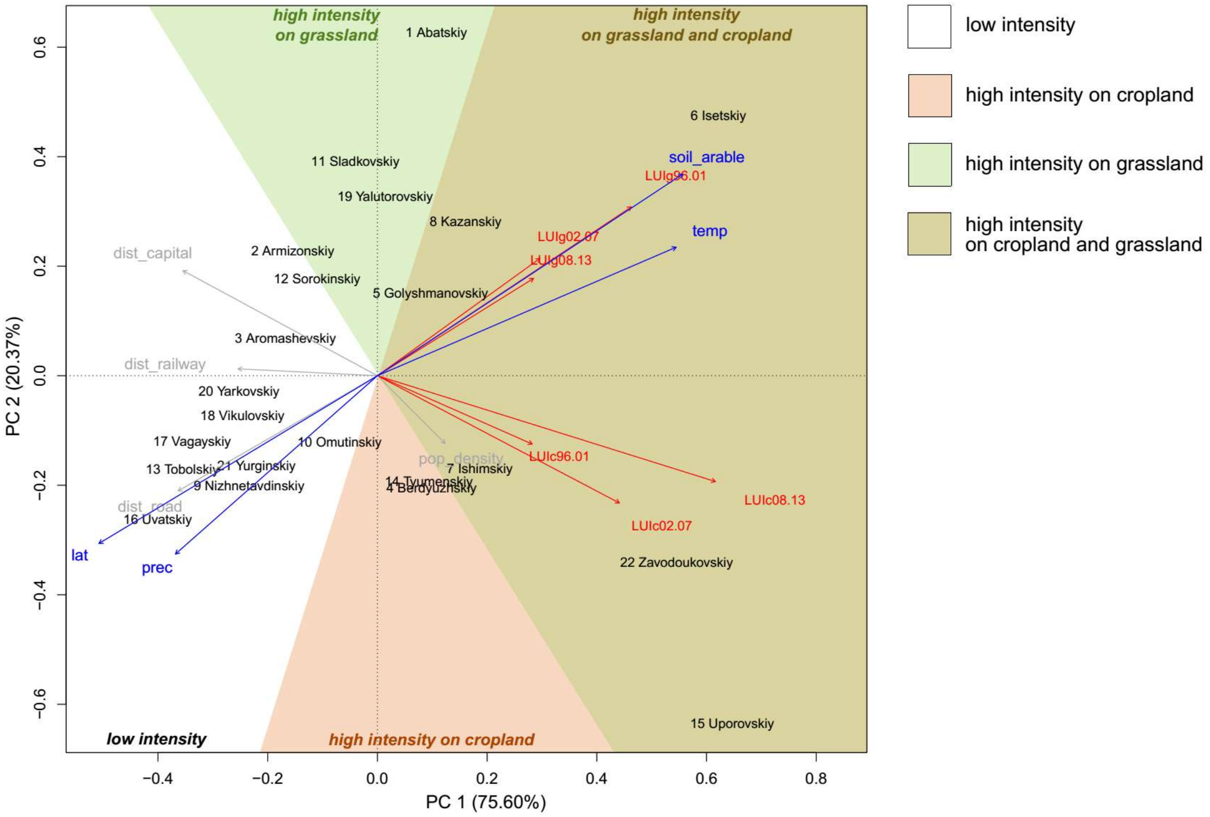

Figure 5: Principal component analysis (PCA) of LUI on cropland (LUIc) and grassland (LUIg) for three periods with fitting of environmental and infrastructure variables in Tyumen province. 'soil_arable': proportion of soils suitable for arable farming; 'temp': mean annual air temperature; 'pop_density': population density; 'prec': mean annual precipitation; 'lat': latitude; 'dist_road': mean distance to nearest main road; 'dist_railway': mean distance to nearest railway; 'dist_capital': mean distance to provincial capital Tyumen. Significant fitted vectors are blue ($p<0.05$), coloured shadings indicate groups of intensity.

Combining the two separate calculations for both land-use types, again the districts located close the Kurgan province border (no. 6, 15, 22) and the surrounding of Ishim (no. 5, 7, 8) were characterised as districts with high intensity. The ordination diagram provides the opportunity to distinguish between districts with predominantly high intensity on grassland (no. 5, 6 and 8) in the upper right quarter and districts with predominantly high intensity on cropland (no. 7, 15 and 22) located in the bottom-right quadrant.

DISCUSSION

From 1996 to 2013 we found a clear temporal trend in increasing LUI on cropland, and a decreasing trend in LUI on grassland in Western Siberia. On the contrary, van der Sluis et al. (2015) detected stabilisation of LUI for the last decade in Europe without a clear trend in one direction or another. The rates of land abandonment were noticeable lower in our study area than in the European part of Russia (Ioffe et al. 2004) and northern Kazakhstan (Kraemer et al. 2015). The change from abandonment into recultivation occurred much earlier in the Western Siberian grain belt than in the rest of Russia. For the European part (Schierhorn et al. 2013; Schierhorn et al. 2014b) as well as the whole Russian Federation (Kurganova et al. 2014) the trend did not yet reverse from cropland abandonment into recultivation.

Cropland intensification

Less effectual drivers of land abandonment may explain lower abandonment rates in Western Siberia compared to European Russia. Negative effects by restricted infrastructural accessibility and market availability (Prishchepov et al. 2013) are likely to be less pronounced in Western Siberia. The agricultural production conditions are overall poorer in that entirely remote and rural region compared to the European part of Russia. Furthermore, the regional proximity to flourishing Russian oil and gas industries north of Tyumen (Khanty-Mansiysk and Yamalo-Nenets Autonomous Regions) may provide investment resources for cropland intensification in Western Siberia. In contrast to little dependencies of agricultural activities on biophysical factors in European Russia (Prishchepov et al. 2013), our PCA showed clear connections between cropland LUI and climate and soil conditions, respectively.

Along with the expansion and intensification of crop production, an increase in crop productivity could be observed for the Western Siberian grain belt. In the long term, crop yields can be used as an indirect indicator for use intensity (van der Sluis et al. 2015). Hence, the reported yields (ROSSTAT 2015) underlined the increasing LUI on cropland. Obviously, higher grain yields are usually gained by increased inputs and often linked to increased environmental damage. For the Western Siberian grain belt it has to be mentioned, that increasing amounts of fertilizers, starting from very low levels, mean initially a development from soil mining towards levelled nutrient balances. Therefore, this part of intensification represents a development towards sustainable soil use. Contrary to environmental problems caused by high nutrient balance surplus in Central Europe, crop production in Western Siberia is primarily limited by water supply (Selezneva 1973). Consequently, a similar development of groundwater pollution by nutrient leaching is unlikely.

Regardless of the described spatial patterns in the Western Siberian grain belt, the overall LUI level is low compared to other arable farming regions (Siebert et al. 2010; Václavík et al. 2013). For instance, Dietrich et al. (2012) modelled in a global estimation intensity levels from 0.79 for the former Soviet Union and 1.34 for Europe in relation to the worldwide average of 1.00. Nevertheless, despite current LUI on cropland in Western Siberia being low, as it steadily increases negative impacts on the environment will also increase. Besides ecological aspects, future strategies for sustainable land management should also cover economic concerns of farmers. One favourable strategy to integrate both aspects can be sustainable intensification (SI) of crop production systems, which means to increase yields without adverse environmental damage (The Royal Society 2009). In particular, in conjunction with climate change predictions of rising temperatures and more frequently occurring draughts (Pilifosova et al. 1997; Degefie et al. 2014), improvement in water use efficiency should become a key issue in Western Siberia. Against the background of semi-arid environments, SI involves rather technical enhancements or breeding progress than increasing inputs like fertilizers or agrochemicals. Since cropland in Western Siberia is prevalently managed in large scales by large agricultural organisations (ROSSTAT 2015), such adaptation strategies could be readily implemented by those well-equipped large enterprises.

Decreasing grassland intensity

The consequences of the state farm system collapse are even more pronounced in terms of animal husbandry. The ongoing decrease in grazing livestock numbers in the Western Siberian grain belt was substantial but below-average compared to European Russia (Ioffe and Nefedova 2004) as well as to the entire Russian Federation (Table 3). In general, also animal husbandry started to rebound slightly after the first decade of post-Soviet agriculture (Liefert and Liefert 2012). By contrast, there has been a significant shift in Western Siberia from land-based cattle farming to housed livestock production of pigs and poultry (ROSSTAT 2015). Furthermore, intensification within dairy farming and cattle fattening in large-scale enterprises strengthens decreasing LUI on grassland by substitution of grazing and hay with forage cultures from cropland and imports of concentrate. For instance in Tyumen province the overall share of concentrate feed increased from 43 to 52 % between 2000 and 2009 (TYUMSTAT 2014).

For the development of sustainable land management strategies, target areas for grassland conservation should be located in regions with less treatment during the Soviet-era (low LUIg in T1) and spatially distinct from regions with high cropland intensity (high LUIc in T3), e.g. districts no. 2, 3, 10, 18 and 21. Moderate grazing pressure is known to have positive impact on grassland biodiversity (Dengler et al. 2014), therefore governmental incentives for the rural population to keep grazing livestock may contribute to the maintenance of grassland ecosystems. However, that might be a difficult task, since urbanisation trends let the rural population shrink also in Western Siberia. Another conceivable approach could be incentives for low intensity land-based cattle farming by larger agricultural enterprises with obligatory summer grazing and hay production.

Since cropland and grassland are both part of a complex and interacting agro-ecosystem, a holistic view would be preferable to separate analysis but difficult to implement. Consequently, strategies for sustainable land management should cover usage activities at all parts of the landscape.

CONCLUSION

Apart from widely studied land-use change by post-Soviet land abandonment, we also determined significant but opposite processes of land-use intensification on cropland and a decrease in intensity on grassland for the Western Siberian grain belt, which necessitates the usage of an individual index for each land-use type.

Future developments of agricultural activities in Western Siberia are difficult to predict, but the continuation of the processes described is likely. Consequently, at the landscape scale a spatial specialisation with ongoing cropland intensification on suitable soils in areas with favourable agro-climatic conditions seems to be preferable to reclamation of abandoned cropland or an expansion of arable land. Again, this intensification path needs to be sustainable, especially in response with climate change.

Our findings clearly show the necessity of a different strategy for future sustainable land management for grassland and cropland, which have to be addressed specifically by the different land users. For further application, these fundamentals could supplement socio-economic approaches and contribute to scenario development for sustainable land use.

ACKNOWLEDGEMENTS

This work was conducted as part of project SASCHA (‘Sustainable land management and adaptation strategies to climate change for the Western Siberian grain belt’). We are grateful for funding by the German Government, Federal Ministry of Education and Research within their Sustainable Land Management funding framework (funding reference 01LL0906D). We thank Johannes Kamp, Norbert Hölzel and Immo Kämpf for fruitful discussions and statistical advice and two anonymous reviewers for their valuable comments.

PICTURE CREDIT

Insa Kühling

Agro-industrial cereal and subsistence hay harvest in Tyumen region, 10 September 2013 and 1 September 2013

2.2 Potential of land-use intensity analysis for sustainable land management scenarios in southern West Siberia

[GEO-ÖKO 36 (2015) 112-132]

AUTHOR CONTRIBUTIONS

Insa Kühling performed the land-use intensity analysis, developed the application possibilities of this analysis and wrote major parts of the manuscript including, in particular introduction and discussion
Yuliana Griewald developed the scenarios and wrote scenario related parts of the material and methods, results and discussion chapters
Gabriele Broll supervised Insa Kühling
Dieter Trautz supervised Insa Kühling

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GEO-ÖKO XXXVI (2015) 112-132

POTENTIAL OF LAND-USE INTENSITY ANALYSIS FOR SUSTAINABLE LAND MANAGEMENTSCENARIOS IN SOUTHERN WEST SIBERIA

POTENTIAL VON INTENSITÄTSANALYSEN FÜR SZENARIEN ZUR NACHHALTIGEN LANDNUTZUNG IN SÜDWESTSIBIRIEN

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Submitted
18 March 2016
Accepted
01 June 2016

Keywords
sustainable land management, cropland, grassland, agriculture, land-use intensity, scenario, landscape planning, Eurasian grain belt, southern West Siberia, post-Soviet

Schlüsselwörter
nachhaltige Landnutzung, Acker, Grünland, Landnutzungsintensität, Szenario, Landschaftsplanung, eurasischer Getreidegürtel, Südwestsibirien, postsowjetisch

SUMMARY

The post-Soviet transition from a planned to a market-driven economy went along with massive land-use changes and implied substantial consequences for agricultural production systems. In this paper, we demonstrate the usefulness of land-use intensity information for the development of sustainable land management (SLM) strategies for Tyumen province, which is centrally located within the Western Siberian grain belt. A quantitative spatio-temporal land-use intensity index enabled us to develop locally adapted scenarios and to identify priority areas for implementation of SLM strategies. We derived two major strategies for future SLM in Tyumen region: low-intensity grazing for grassland conservation and sustainable intensification by adapted farming technology on cropland instead of cropland expansion. These two strategies have to be addressed by the major land users, namely rural households that keep most of grazing livestock and large agricultural organisations, which cultivate the majority of the cropland area. The participatory scenario development process has the potential to draw policy-makers' attention to the benefits of SLM.

ZUSAMMENFASSUNG

Im Zuge der postsowjetischen Transformation von der Planwirtschaft zu einem marktwirtschaftlichen System ergaben sich weitreichende Landnutzungsänderungen mit erheblichen Konsequenzen für die landwirtschaftlichen Produktionssysteme. In diesem Artikel wird für die zentral im Westsibirischen Getreidegürtel gelegene Region Tjumen aufgezeigt, wie mit Hilfe von detaillierten Informationen über vergangene Landnutzungsintensitäten kleinräumig angepasste Szenarien für eine nachhaltige Landnutzung entwickelt werden können. Aus der quantitativen, raum-zeitlichen Intensitätsanalyse wurden darüber hinaus Vorrangflächen zur Umsetzung der nachhaltigen Landnutzungsstrategien abgeleitet. Es wurden zwei wesentliche Strategien identifiziert: extensive Beweidung zum Erhalt der Grasland-Ökosysteme sowie nachhaltige Intensivierung auf Ackerland statt einer weiteren Ausdehnung der Anbauflächen. Diese beiden Strategien sind separat an die jeweiligen Hauptnutzer zu richten: Die grasenden Viehbestände werden überwiegend von dörflichen Selbstversorger-Haushalten gehalten und die Ackerfläche wird weitestgehend von großen landwirtschaftlichen Organisationen bewirtschaftet. Der partizipative Prozess der Szenario-Entwicklung kann zu einer Sensibilisierung der politischen Entscheidungsträger für nachhaltiges Landmanagement beitragen.

INTRODUCTION

The Western Siberian grain belt covers 22.3 million ha cropland in the Asian part of Russia and is therefore of global significance for agricultural production of food and fodder. Agricultural land-use intensity (LUI) is low compared to central Europe (Siebert et al. 2010; Dietrich et al. 2012; Václavík et al. 2013). Furthermore, mosaic patterns of cropland, grassland and forest, which are typical for the forest steppe zone in the south of Western Siberia, provide a high potential for biodiversity conservation.

The post-Soviet transition from a planned to a market-driven economy implied substantial consequences for agricultural production systems. The collapse of the state farm system accompanying the dissolution of the Soviet Union in 1991 went along with massive land-use changes due to rapidly decreasing livestock numbers (ROSSTAT 2016) and widespread cropland abandonment (Prishchepov et al. 2013) in Russia. In Tyumen province, which comprises an essential part of the Western Siberian grain belt, the number of livestock units has stabilised by now and recultivation of ex-arable land has been taking place since. Besides the expansion of the sowing area, also the intensity of permanently cultivated cropland has increased in the past two decades (Kühling et al. 2016). In the future, climate change is expected to bring about a number of challenges for crop production in the area. Regionally downscaled global climate change models predict increasing drought risks and water scarcity (Alcamo et al. 2007; Tchebakova et al. 2011; Degefie et al. 2014). Even though elevated CO_2 levels are likely to compensate for heat stress for some crops (Maracchi et al. 2005), the net effect on food security in Siberia is not clearly positive (Dronin and Kirilenko 2011).

Given the challenges of climate change and increasing demand for agricultural products by a growing world population, concepts of sustainable land management are urgently needed (Tilman et al. 2002; Godfray et al. 2010; Foley et al. 2011; Tilman et al. 2011). Most of the existing frameworks for a sustainable future of agricultural land use pertain to a theoretical and global scale. Within the German-Russian interdisciplinary research project SASCHA, sustainable land management (SLM) strategies were developed on smaller scales, namely, for the field, farm, and district scales of the Tyumen province (SASCHA 2015). These strategies were accompanied by scenarios of regional land use in 2050, allowing an exploration of “alternative worlds” (Westhoek et al. 2006) of rural development and a comparison of a variety of future land-use options (Nassauer and Corry 2004).

The objectives of this paper are (1) to use the knowledge of temporal trends and spatial patterns of land-use intensity to derive sustainable land management strategies, (2) to propose scenario pathways for a participatory landscape planning process and (3) to identify priority areas for SLM implementation.

MATERIALS AND METHODS

Study area

Tyumen province is centrally placed in the Western Siberian grain belt (Fig.1). The grain belt is located in the southern part of the Western Siberian plain bordered by the Urals in the west, and the Altai mountains in the east. The border with Kazakhstan marks the southern boundary, and to the north, the Western Siberian grain belt is marked off by closed forests of the taiga ecozone (boreal forest zone). Agriculture dominates in the forest steppe zone but is less pronounced within the pre-taiga further north. The climate is continental and semi-arid in the south-east and more humid in the north and at higher elevations (Trabucco and Zomer 2009). Mean annual temperatures range from -6.9 °C in the north and

Fig.1: Location of the Tyumen within the provinces of the Western Siberian grain belt.
Abb.1: Lage von Tjumen innerhalb der Provinzen des Westsibirischen Getreidegürtels.

towards higher elevations to +4.5 °C in the south-east, and the mean annual precipitation ranges from 268 mm to 904 mm (WorldClim 2013). Due to the short growing seasons, arable farming is dominated by summer crops, mainly spring wheat (Selezneva 1973; Mueller et al. 2015).

Tyumen province consists of 22 districts that have a homogeneous but relatively poor infrastructure network of paved roads and the southern districts are connected to the Trans-Siberian Railway (ROSREESTR 2014). Every district has a centrally located regional capital, and each grain-producing district possesses a grain storage facility built back in the Soviet times, mostly with a railway connection. The population of the region comprises about 1.4 million inhabitants, having now reached its early 1990s levels after a drop in the mid-2000s (ROSSTAT 2016). The rural landscape is sparsely inhabited with 6.2 people per km² except for the provincial capital vicinities, which have a higher population density of 185.1 persons per km² (TYUMSTAT 2014). The share of agriculture, hunting and forestry in the gross regional product comprised 3.8 % in 2013 (compared to 4.2 % in Russia overall), with a decreasing trend over the past years (ROSSTAT 2016). Russia's flourishing oil and gas industries in the north of Tyumen province (Khanty-Mansiysk and Yamalo-Nenets Autonomous Regions, Fig.1) serve as an extraordinary driver for economic development and impact also the agricultural sector of the region (Dronin and Kirilenko 2008; Dronin and Kirilenko 2011).

Data sources used

For our analysis we used subnational annual statistical data from the Russian Federal State Statistics Service, downloaded from www.fedstat.ru and www.tumstat.gks.ru. These governmental data source have been reported to be reliable in the area of agriculture (Schierhorn et al. 2013). Within their agricultural statistics the Federal Statistic Service distinguish between three farm types based on their legal form: agricultural organisations, peasant farms and households. Agricultural organisations are typically large-scale enterprises of a joint-stock type managing large units of livestock and/or cultivating vast cropland areas. Peasant farms emerged with the dissolution of the

Soviet Union and essentially denote family farms. Household production refers to subsistence agriculture, which is characteristic for most rural households.

Based on these data we used the spatio-temporal quantification of land-use intensity from Kühling et al. (2016) for scenario development. From 1996 to 2013 two separate input-oriented indices for cropland and grassland were calculated. As input factors on cropland, we used the total amount of fertilizer (sum of nutrients from organic and mineral fertilizer), the proportion of sowing area and the proportion of sown grain crops. The latter parameter was used because the substitution of perennial forage crops by annual grain crops leads to shorter crop rotations and a higher frequency of tillage operations, which indicates a higher LUI. For grassland, we aggregated cattle, sheep, goats and horses to grazing livestock units, weighted after EUROSTAT (2014). As cattle from large agricultural enterprises are rarely grazed, only livestock kept by households was considered. Spatial distribution and area shares of land-use types were derived from a 30m resolution global land cover map from 2010 (www.globeland30.com; NGCC, 2014). To derive spatial information about priority areas for different sustainable land management strategies we used a classification into intensity groups by a principal component analysis of LUI with post-hoc fitting of environmental and infrastructural parameters (see Kühling et al. (2016) for details).

Scenario development

Revealing the recent developments and current patterns, the land-use intensity analysis can be meaningfully used to sketch and visualise potential future developments in the region, which, in turn, could function as a tool in participatory processes with local stakeholders. Scenarios serve well for this purpose, understood as as 'coherent, internally consistent and plausible descriptions of possible future states, for example of land use in a region' (Hauck and Priess 2013), including the paths leading to these future states. The scenarios developed for the Tyumen province were drafted, debated, and adjusted by an interdisciplinary team in an iterative manner, and relied upon several methodological aspects.

First, the focus is placed on land use and the concomitant farm management practices, in line with the idea that scenarios cover 'specific, clearly demarcated segments of reality' (Kosow and Gaßner 2008) rather than a lot of potentially relevant aspects. Each scenario, however, covers a range of dimensions beyond land use itself – for instance, type of agricultural policy, demographics and organisational forms in agriculture, biodiversity as well as soil and water quality. Second, and equally important, each scenario is not just a snapshot of a possible future state: it also covers the development of key factors from the starting point (i.e. now) until a particular year in the future. Third, to understand the span of the proposed scenarios, it is important to keep in mind that scenarios are not predictions about expected future developments which can be e.g. extrapolated from observable trends (see Hauck and Priess 2013). Instead, they are applied when uncertainties concerning several parameters are high and predictions impossible. Hence, we will focus on the more probable developments only. Also, we introduce scenarios that are, from the current viewpoint, less likely and not necessarily desirable. Contrasting a broad range of scenarios has the potential to show particularly vividly how various events and decisions, in particular policies, lead to diverging outcomes, thereby considering their desirability and implementation requirements. Fourth, the time horizon plays an important role in scenario development. On the one hand, it should allow enough time for significant developments to take place, so that the outcomes are sufficiently diverse to be compared. At the same time, it should be close enough to evoke the sense of attachment as well as ability to have some influence on the course of events. For our purposes the year 2050 appears appropriate.

RESULTS

Agricultural structures and changes

Current agricultural structures were characterised by coexistence of large-scale agricultural enterprises and firmly established rural subsistence agriculture. Agricultural organisations cultivated 96 % of the cropland in Tyumen province, predominantly with modern large-scale farming equipment and in units up to 60,000 ha. In addition, livestock is kept in large stocks (more than 100,000 pigs, 2,500 dairy cows or 1 million broilers). Households kept 55 % of the total livestock in smallest units (1 dairy cow, 2 pigs, 6 hens) for subsistence and local market production. They dominated the usage of grasslands by community

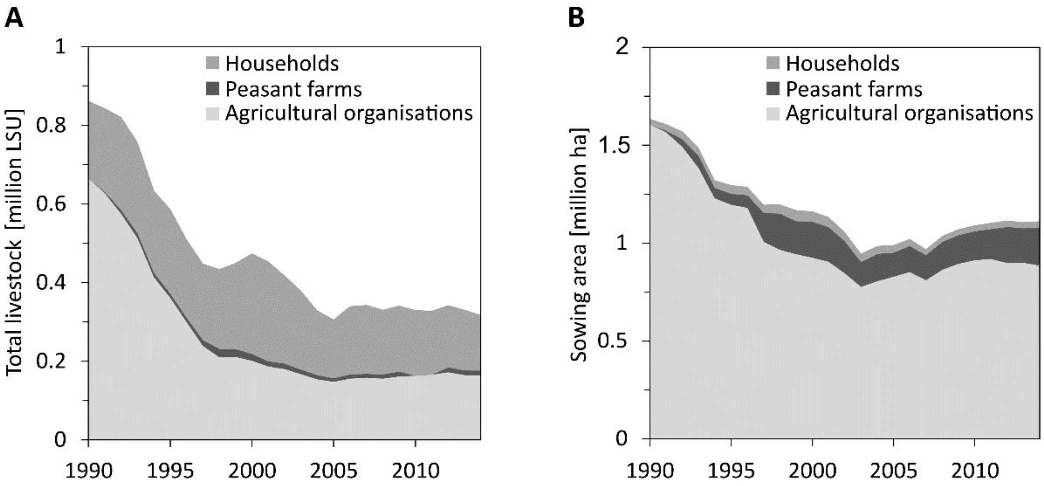

Fig.2: Total dimension and share of different farm types in animal husbandry (A) and arable farming (B) in Tyumen province since dissolution of the Soviet Union. Source: ROSSTAT (2016).

Abb.2: Gesamtes Ausmaß und Anteil der verschiedenen Betriebstypen für Viehhaltung (A) und Ackerbau (B) in der Provinz Tjumen seit Auflösung der Sowjetunion. Quelle: ROSSTAT (2016).

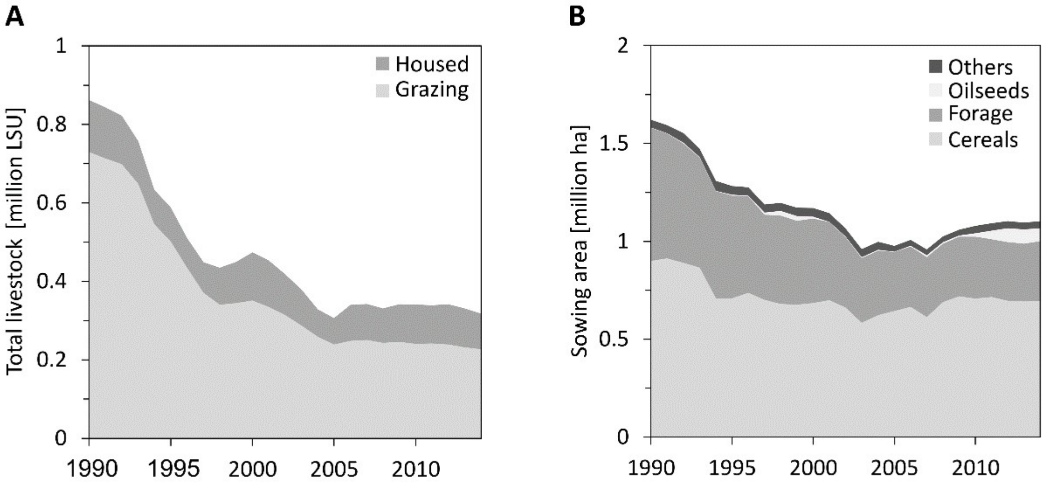

Fig.3: Total livestock numbers with share for grazing (cattle, sheep, goats, horses) and housed (pig, poultry) in normalized livestock units (A) and total sowing area with share of different crops (B) in Tyumen province. Source: ROSSTAT (2016)

Abb.3: Gesamtviehbestand mit Anteilen der weidenden (Rinder, Schafe, Ziegen, Pferde) und im Stall gehaltenen (Schweine, Geflügel) Tiere in Großvieheinheiten (A) sowie die gesamte Aussaatfläche mit Anteilen der einzelnen Feldfrüchte in der Provinz Tjumen. Quelle: ROSSTAT (2016)

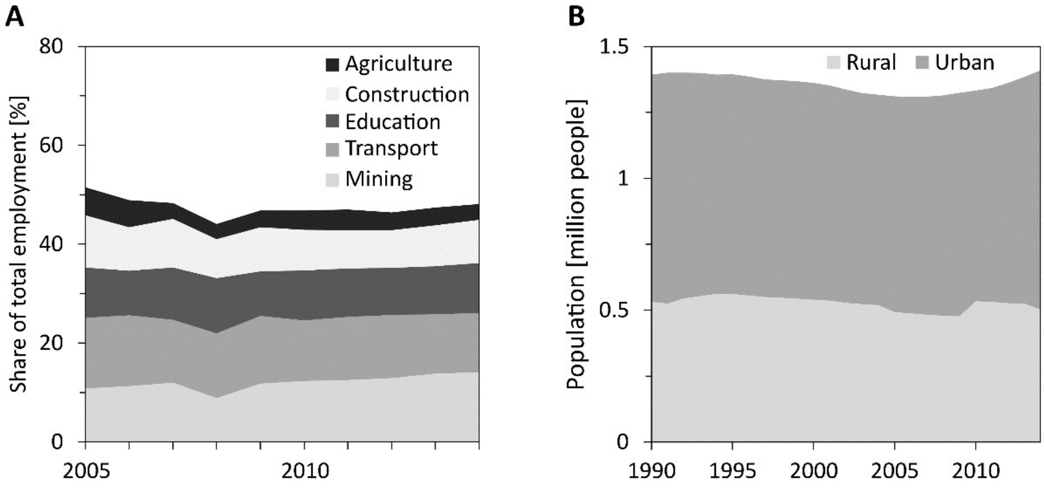

Fig.4: Share of employment in selected economic sectors (A) and population dynamics (B) in Tyumen province. Source: ROSSTAT (2016)

Abb.4: Beschäftigungsanteile in ausgewählten Wirtschaftszweigen (A) und Bevölkerungsentwicklung (B) in der Provinz Tjumen. Quelle: ROSSTAT (2016) grazing and hay production around the villages, whereas the big enterprises mostly fed their animals with fodder produced on arable land (ROSSTAT 2016). These ratios changed only marginally during the last two decades (Fig.2A). Peasant farms played a minor role especially in the sector of livestock farming, since they only kept a marginal share of the total stocks. . In terms of arable farming, they managed 13 % of the total cropland area (Fig.2B) at intermediate levels of mechanisation, typically with less modern machinery than the large enterprises.

After the collapse of the state farm system, total livestock numbers demonstrated a clearly decreasing trend in, but also a significant shift from grazing livestock (cattle, sheep, goats, horses) to housed livestock (pigs, poultry) took place (Fig.3A). Whilst in 1990 86 % of the total livestock was grazing, the proportion shrunk to 71 % in 2014. In the absence of reliable data about poultry stocks, this ratio underestimated the housed livestock. This had impact on both land-use types, grassland and cropland since housed livestock production can take place on a landless basis, by importing grain feedstuff. Furthermore, the concentrate in the feed rations for the ruminants increased over time (TYUMSTAT 2015).

In Tyumen province, the trend of post-Soviet land abandonment reversed into re-cultivation of ex-arable land in the early 2000s. Compared to size of 1.6 million ha in 1990 (set to 100 %), cropland area fell to the lowest extent by 59 % in 2003 and increased to 68 % in 2013 (TYUMSTAT 2015; Fig.3B).

The share of agricultural employment was small compared to the rest of the Western Siberian grain belt ranging behind employments connected to oil and gas industries in northern autonomous regions of Tyumen province (Fig.4A). Mining and transport represent the largest employment sectors with increasing trends, whilst the share of employment in agriculture, hunting and forestry saw a decrease from 5.7 % in 2005 to 3.2 % in 2014. Furthermore, Tyumen province is among the few centres with a growing population trend across all Russia (ROSSTAT 2016; Fig.4B). Nevertheless, the share of the rural population in 2014 decreased by 6 % compared to 1990, following the general trend of urbanisation.

Land-use intensity

Beyond a simple look at the sowing areas and livestock numbers, a detailed analysis of land-use intensity on the two different land-use types (grassland and cropland) showed these divergent trends: A highly significant increase in cropland intensity and a less steep but also highly significantly decreasing trend in grassland intensity (Fig.5).

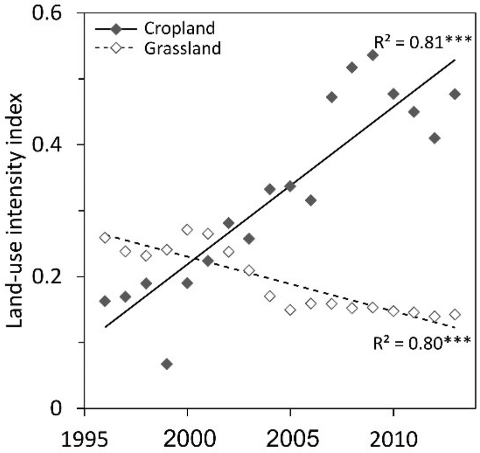

Fig.5: Temporal (linear) trend of land-use intensity indices on cropland and grassland in Tyumen province. ***: significant at $p<0.001$.
Abb.5: Trend (linear) der zeitlichen Entwicklung von Landnutzungsintensitäten auf Acker und Grünland in der Provinz Tjumen. ***: signifikant mit $p<0.001$.

Both trends to a large extent implied negative impacts on the environment, as cropland intensification translates into higher inputs of fertilizer and less agro-biodiversity due to more homogeneous cropping systems, while reduced grazing pressure on grassland leads to succession, also causing biodiversity loss. Patterns in the individual districts of Tyumen province followed the average trend, except the northern part where no agriculture takes place.

For sample spatial planning and scenario development, five very diverse districts to the southeast of Tyumen were selected (Fig.6). Here we found a wide range of developments, from stagnation to high increase on cropland and different levels of decreasing intensity on grassland (see Kühling et al. (2016) for details).

The separate investigation of grassland and cropland could be integrated by a principal component analysis. Besides plausible explanations of environmental and infrastructural influences (Kühling et al. 2016), this approach enabled us to identify priority areas for sustainable land management strategies. Fig.6 shows a grouping into four classes for the districts of Tyumen province: those with overall low intensity, mostly located in the northern region with less suitable agro-climatic and biophysical conditions, and three groups of high intensity. The latter could be differentiated based on whether the intensity was predominantly high on grassland or cropland or on both.

Scenarios for sustainable development/land management

The land-use intensity analysis vividly demonstrated divergent developments on cropland and grassland in the post-Soviet period. In order to assess the possible future developments on grassland and cropland as well as their effects on biodiversity, land-use scenarios appear appropriate. Within the methodological scenario framework and based on the land-use history, we developed four land-use scenarios for the Tyumen province in 2050, which cover a range of potential developments from conventional cropland intensification to a large-scale abandonment of cropland, and from grassland abandonment to grassland restoration within a low-intensity livestock management scheme.

Scenario 1 represents a continuation of the currently observable trends of cropland intensification and grassland abandonment. In 2050, the cultivated area is back at its 1990s levels and agro-biodiversity falls to a level comparable with that of intensively used monocultures. Animal husbandry is likewise highly industrialised, and grassland abandonment leads to alarming levels in terms of floral biodiversity. Large-scale enterprises dominate the rural landscape, and their main goal is production increase. These developments are in line with the federal and regional agricultural policy, which supports grain production as well as national and regional self-sufficiency in agricultural products. Thanks to relatively stable economic growth, the regional government can afford to support its agricultural producers in acquiring mineral fertilizers, pesticides, and large-scale machinery. In terms of the rural population, this scenario implies out-migration as highly mechanised enterprises offer only a limited number of jobs.

Scenario 2 describes a situation in which environmental issues have over time won in importance on the national and regional agenda. Nature conservation is integrated in a range of policies, and in particular agro-biodiversity, soil conservation and prevention of groundwater pollution represent key conditions of state support to farms. Accordingly, agricultural producers organise their operations in a manner which allows them to improve productivity while balancing it against environmental impacts of their activities. The total cropland area is somewhat smaller, while the grassland area is somewhat larger than in Scenario 1. Medium- and large-scale farms represent the key types of agricultural producers. Migration from the rural areas is slightly weaker than in 2015 as people are employed on a larger number of medium-sized farms.

Scenario 3 emerges in the conditions of long-term economic stagnation, when the state cannot afford to sufficiently support agricultural producers. With a significant number of large-scale enterprises going bankrupt over time, the rural landscape is characterised by a large number of household plots intensively using their land to grow vegetables and to a small extent grains, whereas large areas of former cropland lie fallow. The size of grasslands is slightly larger compared to 2015, since most families keep cattle as part of subsistence agriculture (but others rely on imported foodstuffs). Both irregular mowing practised by the households and cropland abandonment have positive effects on biodiversity. A large share of the previously rural population now lives in urban areas, and some commute to the northern districts to work outside of agriculture.

Scenario 4 features an improvement of environmental standards in agricultural production with a simultaneous economic decline. Here, two periods are distinguishable. In the first period, as the economy flourishes around 2030, quality certification schemes in agriculture are introduced. In particular, demand for high-quality livestock products on Russian and international markets induce the establishment of certification schemes in organic farming and low-intensity livestock management. However, a series of economic crises follow, severely curbing the capacities of the state to support agricultural producers in the region. As a result, in the second period, i.e. around 2050, a large number of agricultural producers leave Tyumen agriculture and the rural population decreases as employment opportunities shrink. The key profit-making agricultural producers in the region are participants of certification schemes for low-input livestock management with well-established contacts to customers abroad. These export-oriented producers together with household plots remain the main types of agricultural. The landscape pattern under these conditions is characterised by a significant increase in the size of meadows and pastures and a sharp decline in the size of cropland, with strong positive effects for floral biodiversity.

These four storylines, drawing on a broad range of potential developments, demonstrate a diversity of possible futures in the rural areas of Tyumen province.

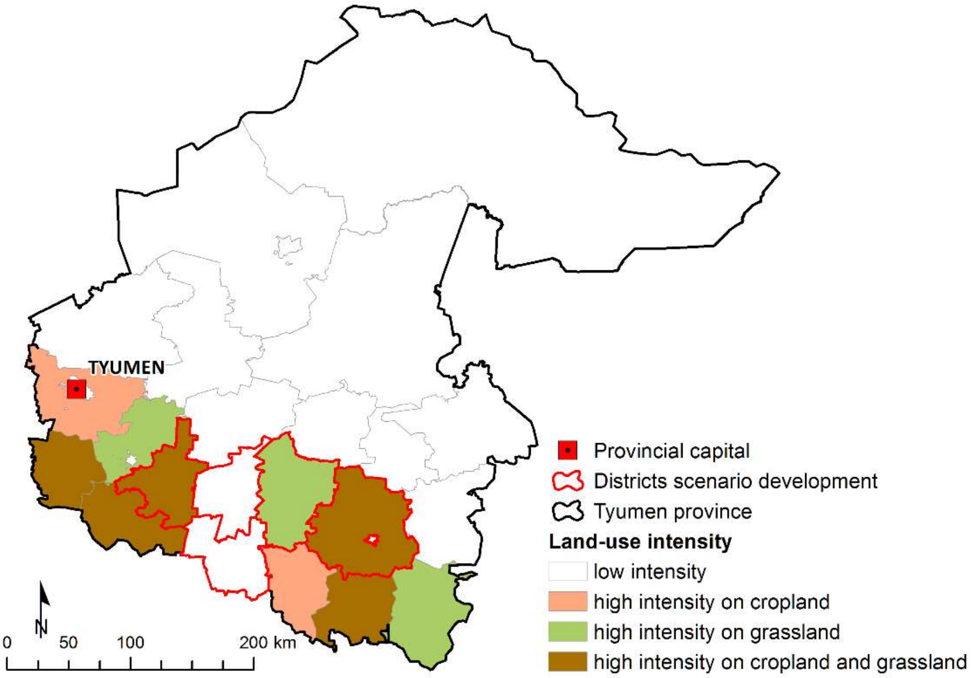

Fig.6: Priority areas for sustainable land management strategies derived by principal component analysis of land-use intensity in the districts of Tyumen province from 2008-2013.
Abb.6: Vorrangflächen für Strategien zur nachhaltigen Landnutzung abgeleitet aus einer Hauptkomponentenanalyse der Landnutzungsintensitäten in den Distrikten der Provinz Tjumen von 2008-2013.

Depending on the different land-use intensity histories and biophysical conditions, each district may show individual future characteristics.

DISCUSSION

Drivers of land-use change

Compared to other agriculturally important regions of the former Soviet Union, the development of land use in Tyumen was different. For example, the maximum share of abandoned land was noticeably lower than in the European part of Russia (Ioffe and Nefedova 2004) or in northern Kazakhstan (Kraemer et al. 2015). Furthermore, the inversion from abandonment into recultivation of ex-arable land started earlier in Tyumen (Schierhorn et al. 2013; Kurganova et al. 2014). Smaller barriers for recultivation in Tyumen could be explained by more homogeneous agro-climatic and infrastructural conditions across the Western Siberian plain compared to the European part. Due to the overall poorer conditions for agricultural production, land abandonment was less driven by bio-physical and agro-climatic conditions, so that the threshold for reversion was lower than in European Russia (Prishchepov et al. 2013). Moreover, the exceptional situation of Tyumen agriculture is connected to budgetary advantages stemming from the oil-producing industries in the northern part (Dronin and Kirilenko 2011). This also plays an important role in the much higher Human Development Index of the Tyumen province compared to the rest of the country: Tyumen occupies the third place in the ranking of Russian regions, after Moscow and St. Petersburg (Mueller et al. 2015).

Land-use types like grassland and cropland are only parts of the entire agro-ecosystem and interact in a complex way (Tscharntke et al. 2005). Therefore, for developing sustainable land management strategies a holistic approach embracing both land-use types would be desirable. However, such an approach appears challenging in our case, since not only the developments on grassland and cropland were opposite but also two completely differently structured user groups managed these land-use types. Consequently, we first focused on separate strategies for each land-use type that could be addressed by the specific users, namely large agricultural enterprises and households, and then brought them together under the umbrella of land-use scenarios.

Strategies for sustainable land management

Grassland management

Grassland is known to have a high ecological value and especially low-intensity grazing pressure has positive effects on the maintenance of floral biodiversity (Dengler et al. 2014). These effects were also observed by Mathar et al. (2015) for three test areas (400 km² each) along a climate gradient in Tyumen. Especially within the agricultural landscape, small forest surrounded remnants of grassland which have never been cultivated were found have a very high species richness (Mathar et al. 2015). Investigations about recovery of grassland vegetation on abandoned cropland by Kämpf et al. (2016) revealed a high conservational value already after short time of abandonment. Therefore, these ex-arable fields have to be included in measures for sustainable grassland management.

The general trend of grassland cultivation showed a steep decrease of grazing pressure since breakdown of the Soviet Union due to massive decline in livestock numbers, particularly ruminants. To avoid negative impacts of continuing abandonment and succession, specific grassland management strategies are needed. Against the trend of urbanization, which comes along with shrinking rural population, governmental incentives could help to sustain or even increase the community grazing in the villages. Also subsidies for low-input grazing systems with obligatory summer grazing and hay production in larger scales, addressed to agricultural enterprises – specifically peasant farms – could contribute to the preservation of grassland ecosystems

Cropland management

To meet the future demands of food and fodder by a growing world population, different strategies of cropland management are discussed (Godfray et al. 2010). In Tyumen, ex-arable fields showed significant higher floral biodiversity compared to arable fields (Kämpf et al. 2016c). Hence, an efficient arable farming or intensification on existing cropland seems to be preferable over expansion of cropland into abandoned areas. In the case of intensification, this has to be done in an environmental friendly way to meet the aims of SLM (Tilman et al. 2002; Tilman et al. 2011). In Western Siberia, negative environmental impacts of agricultural intensification by high nutrient balance surplus and groundwater pollution are likely to be less pronounced than in Central Europe. Due to the continental climate, arable farming in Western Siberia is primary limited by water supply (Mueller et al. 2015). That means that even increased doses of mineral fertilizers will not produce higher yields, as the nutrient transport is water limited as well. Moreover, high evaporation rations in summer and frozen soils in winter prevent nitrate leaching. Therefore, intensification measures mainly focus on technological adaptations. No-till farming is known as a cropping system, which can provide higher yields under semi-arid conditions (Pittelkow et al. 2015). Increased water-use efficiencies by reduced tillage intensity coincidently enhance the nutrient use efficiencies in semi-arid environments and therefore are both, ecological as well as economically efficient. In particular regarding the climate change predictions of warmer and drier climate for Tyumen province (Tchebakova et al. 2011; Degefie et al. 2014), water use efficiency will become a key issue in future crop production.

Field trials from Western Siberia showed a high potential to save soil water by reduced tillage intensity. Field trials under on-farm conditions over three years near Ishim (south-eastern part of Tyumen province) showed the good possibility to save soil moisture with no-till farming under Siberian conditions (Kühling and Trautz 2015b). Grunwald et al. (2015) also reported from Altayskiy kray beneficial effects from no-till systems, in particular from the extremely dry year 2012. Results from long-term field trials from experimental stations in Northern Kazakhstan reported for sandy textured soils unrestricted potential to increase yields (Suleimenov et al. 2015). Also for loamy to clayey textures in Western Siberia they found yield improving potential but with the need of additional fertilizer applications. In summary Suleimenov et al. (2015) emphasised the important contribution of no-till farming to the system of conservation agriculture for more resilience in cropping systems of Western Siberia. Under the perspective of climate change, the advantages of no-till against traditional tillage are likely to increase in cereal production systems (Pittelkow et al. 2015). The contribution of no-till technology to SLM is only one strategy among others, which are all needed to meet the future demands. Further perspective improvements in arable farming could be expected by new regional adapted genotypes, new types of controlled-release fertilizers further development of precision farming applications and general logistic optimisations.

Summarised, sustainable intensification strategies for cropland in Western Siberia involves rather technical enhancements like reduced tillage intensity or breeding progress than solely increasing inputs like fertilizers or agrochemicals. Such measures like no-till farming systems are readily implementable, as most of the cropland in Tyumen province cultivated in large scales by well-equipped agricultural organisations.

Integration in scenarios

Scenarios can serve as an effective tool to sensitise stakeholders to a range of issues as well as to visualise some potential outcomes of their actions in the future. Especially because scenarios incorporate several dimensions beyond land use itself, such as demographics, policies, and economic situation in the region, they possess strong communicative power (Hauck and Priess 2013). When highly diverse options are presented next to each other, the contrast becomes more intense and the implications more clearly distinguishable. In case if stakeholders come to prefer the more sustainable land-use options, a detailed approach to how they can be implemented needs to be elaborated. In this sense, scenarios are particularly well-suited as a preliminary step before sustainable land management strategies can be discussed (Nassauer and Corry 2004).

To achieve broader acceptance among the local stakeholders, scenario development can be based on historical information that the stakeholders trust. Nassauer and Corry (2004) also highlight the importance and usefulness of detailed information about the past in their scenario framework. The connection with the different LUI history on a district level allowed us to focus scenarios on smaller scales (Zurek and Henrichs 2007). Focussing on the five districts for detailed scenario development (Fig.6), we could derive different recommendations for SLM strategies based on the history of land-use intensity. In the eastern- and western-most districts with a high intensity on both grassland and cropland in the past, Scenario 2 complemented by certain aspects from Scenario 4 would shape a more sustainable future. In those districts that had an overall low LUI in the past because of poor biophysical and infrastructural conditions, Scenario 3 is most likely and would be a beneficial contribution to sustainable land management. For the district with a high intensity on grassland but low cropland intensity Scenario 4 could be a valuable option, since low-intensity grazing is likely to be valuable for biodiversity conservation specifically in areas remote from intensive arable farming (Mathar et al. 2015). Against the background of sustainable land management, Scenario 1 would be undesirable for any district.

CONCLUSION

For Tyumen province we demonstrated the usefulness of land-use intensity information for the development of land management strategies. The detailed quantitative spatio-temporal land-use intensity index enabled us to develop locally adapted scenarios and was used to identify priority areas for implementation of SLM strategies. In an interdisciplinary exchange within the SASCHA project we derived two major strategies for sustainable land management in Tyumen region: (1) low-intensity grazing for grassland conservation as considered in Scenario 4 and (2) sustainable intensification by adapted farming technology for efficient cropland cultivation as reflected in Scenario 2 instead of area expansion. These two strategies have to be addressed by the major land users, namely (1) rural households and (2) large agricultural organisations. The scenario framework has the potential to draw policy-makers' attention to the benefits of targeted land management strategies in the districts with varying land use intensity conditions.

ACKNOWLEDGEMENTS

This work was conducted as part of project SASCHA (‘Sustainable land management and adaptation strategies to climate change for the Western Siberian grain belt’). We are grateful for funding by the German Government, Federal Ministry of Education and Research within their Sustainable Land Management funding framework (funding reference 01LL0906D). We thank Sandra Fleischer for contributing to earlier drafts of the scenarios.

PICTURE CREDIT

Insa Kühling
Sowing no-till and conventional tillage, 19 May 2015

2.3 Impact of tillage, seeding rate and seeding depth on soil moisture and dryland spring wheat yield in Western Siberia [Soil Till Res 170 (2017) 43-52]

AUTHOR CONTRIBUTIONS

Insa Kühling developed the experimental design, conducted the trial, sampled and analysed all data and wrote the manuscript
Dmitry Redozubov assisted with the installation of the field trial in 2015
Gabriele Broll supervised Insa Kühling
Dieter Trautz contributed to the development of the experimental design and supervised Insa Kühling

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Soil & Tillage Research 170 (2017) 43-52

IMPACT OF TILLAGE, SEEDING RATE AND SEEDING DEPTH ON SOIL MOISTURE AND DRYLAND SPRING WHEAT YIELD IN WESTERN SIBERIA

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Submitted
2 December 2016
Accepted
21 February 2017

Keywords
no-till, direct seeding, conservation agriculture, water use efficiency, climate change, sustainable land management

DOI: 10.1016/j.still.2017.02.009

ABSTRACT

Dryland crop production in the Western Siberian grain belt is an important contribution to Russia's growing importance as a global wheat supplier. After the break-up of the Soviet Union significant changes in agricultural structures with recent intensification on cropland took place. Together with climate change predictions of drier and warmer growing conditions, this leads to upcoming challenges for water-limited crop production in the south of the Asian part of the Eurasian grain belt. A full-factorial field trial was conducted on a farmer's field to test adaptations of tillage (usual conventional tillage 'CT' vs. no-till 'NT'), seeding depth (usual deep 6.5 cm vs. shallow 4.5 cm) and seeding rate (usual high 600 grains m^{-2} vs. reduced 450 grains m^{-2}) for potential to increase water use efficiency and grain yield in spring wheat. Results from two above-average wet and cold growing seasons showed significant better soil water storage of NT (+40 %) and no adverse effect on spring wheat grain yield and grain quality for the study site in the south of Western Siberia. Variations in seeding rate of the regional variety were compensated by different manifestation of the individual yield components: high seeding rates resulted in more reproductive ears per m^2 whilst reduced seeding rates produced more grains per ear. The traditional deep seed placement was found to be beneficial for NT but shallow placement was advantageous with CT. The highest yields of 3.19 and 3.82 t ha^{-1} were observed in 2014 with NT, deep seed placement and high seeding and in 2015 with NT, deep seed placement and reduced seeding rate, respectively. The on-farm field trial results revealed, that NT can be successfully used in dryland cropping under current agro-climatic conditions of Western Siberia and is a promising perspective under climate change predictions.

INTRODUCTION

Dryland crop production in the Western Siberian grain belt is an important contribution to Russia's growing importance as a global wheat supplier (Liefert et al. 2010). After the break-up of the Soviet Union and the collapse of the state farm system, significant changes in agricultural structures took place. In the Western Siberian grain belt, land-use intensity on cropland increased significantly since the beginning of the 2000s (Kühling et al. 2016). Recultivation of abandoned cropland and rising inputs of agrochemicals not only increased production output (ROSSTAT 2016) but also led to more adverse environmental impact. Regional downscaling of general circulation models predict increasing drought risks and water scarcity for this area (Alcamo et al. 2007; Degefie et al. 2014). Together, these changing conditions require a sustainable shape of future dryland cropping systems in Western Siberia. Due to high conservational value of non-agro-ecosystems in the forest steppe zone of south Western Siberia, a sustainable intensification (The Royal Society 2009) on agricultural land seems preferable over recultivation or reclamation of additional land (Kämpf et al. 2016c).

Water is the most limiting factor for dryland farming under semi-arid conditions (Nielsen et al., 2002; O'Leary and Connor, 1997; Stewart et al., 2006). The most important improvements for sustainable intensification of crop production in semi-arid environments are increased water-use efficiency and reduction of fallow years by implementing of conservation agriculture (CA) (Lenssen et al. 2007). Following the definition by FAO (2015), CA consists of three important components: (1) continuous minimum soil disturbance by direct seeding ("no-till", NT); (2) permanent organic soil cover; (3) diverse crop rotations. Previous studies (e.g. Pittelkow et al., 2015; Toliver et al., 2012) have shown that NT has different effects on yields subject to boundary conditions such as soils and climate. For dry rainfed cereal production, however, positive yield effects of NT compared to conventional tillage (CT) were possible (Pittelkow et al. 2015), mainly by better capture and storage of plant available water (Lenssen et al. 2014). When NT was combined with the two other principles of CA, results from a global meta-analysis revealed significant increases in crop productivity (by 7.3 %) for dryland environments (Pittelkow et al. 2014). Hence, for these regions CA may be a suitable contribution to sustainable agriculture (Hobbs et al. 2008) and an interesting adaptation strategy to predicted climate-change effects for the Western Siberian grain belt.

NT provides a permanent residue cover by leaving up to 90 % from previous crops on the soil surface (Lal et al. 2007). Hence, not only higher soil moisture but also better erosion protection, carbon sequestration and fuel savings are positive effects of NT compared to CT(e.g. Lenssen et al., 2014; Powlson et al., 2014; Qi et al., 2013; Sainju et al., 2009). On the contrary, increased use of herbicides and development of herbicide resistant weeds are known to come along with conversion from CT to NT (O'Donovan et al. 2007). To balance the net benefits, a holistic view on the complete cropping system is necessary. This means to evaluate NT always within the principles of CA, based on residue management and diverse crop rotations including legumes as substitution of bare fallows (Lal et al. 2007).

Only few results from NT field trials in Russia have been reported in international literature, but comparable studies are available from the northern Great Plains in the USA and Canada and Scandinavia, where short season spring wheat production in high latitudes is similar to Western Siberia (Morgounov et al. 2010). Under the given agro-environmental conditions in the south of Western Siberia NT - if implemented within the system of CA (Giller et al. 2015) - could be a promising contribution to sustainable intensification of agricultural production.

The objectives of this study were to evaluate the potential of NT in dryland agriculture of Western Siberia as contribution to sustainable land management under climate change effects. Therefore, we investigated the effects of tillage, seeding depth and seeding rate on soil moisture and grain yield of spring wheat in a field trial to identify the most water-use efficient combination as adaptation strategy.

MATERIALS AND METHODS

Study area

The trial was located on a farmer's field (56.17 °N, 69.49 °E) near the city of Ishim (Tyumen region) in the south of the Western Siberian plain. The area has a dry sub-humid climate (Aridity index 0.63, Trabucco and Zomer, 2009) within the temperate continental zone (Dfb) (Peel et al. 2007). From the mean annual precipitation of 395 mm, 67 % of which occurs in the long term average within the vegetation period, the remaining third as winter snowfall (TUTIEMPO 2016a). Mean annual air temperature is 1.9 °C, ranging from -16.2 in January to 19.1 °C in July (TUTIEMPO 2016a). The soil water storage (SWS) is primarily filled during snowmelt, whereas summer precipitation becomes only a small share of plant available due to evaporation losses by high air temperatures (Stewart et al. 2006; Wall et al. 2007). The long term mean (1981-2010) weather data shows that the vegetation period on a 5 °C base (McMaster and Wilhem 1997) is 171 days between end of April until beginning of October with 1576 growing degree days (GDD) (TUTIEMPO, 2016). Spring wheat is

Table 1: Soil texture (%) from a reference soil profile located in the centre of the field. Analysis was done before starting the trial in spring 2014.

Soil layer [cm]	Sand [%]	Silt [%]	Clay [%]
0 - 30	17	49	34
30 - 40	13	35	52
40 - 50	21	32	47
50 - 80	37	26	37

usually sown after May 15th, because of field trafficability.

The soil of the experimental field is classified as Phaeozem after the world reference base (FAO 2014) with silty clay loam texture in the topsoil and clay loam to clay in the subsoil layers (**Table 1**). According to the novel Russian taxonomy, the soil is categorised as ‘Agrochernosem’ (INFOSOIL 2016). The organic matter content of the topsoil was 7 %, pH ($CaCl_2$) 6.05 and bulk density 1.32 g cm^{-3}.

Typical cropping systems in the forest steppe region of the Western Siberian grain belt consists of a year with bare (summer) fallow with mechanical weed regulation every 3 to 6 weeks - partly with organic fertilizer application - followed by several years of spring cereals, mostly wheat (Suleimenov et al. 2005; Gamzikov and Nosov 2010; Suleimenov et al. 2010). Partly, the fallow year is substituted by field pea or rape seed, but approximately 10 % of the cropland area in the study region is used for manure deposition during one summer season every 4th to 10th year, with a clear gradient from the manure storage to the more remote located fields.

Experimental design and crop management

The trial was conducted as randomised complete block design with 3 replications in a split-split-plot arrangement. Tillage system was the main plot, seeding depth as sub-plot and seeding rate as sub-sub-plot. Each plot was measuring 24 m by 200 m, sampling and monitoring took place on the centre 20 m by 100 m area on 3 randomly distributed GPS observation points in each plot. **Table 2** provides detailed information about the 8 individual treatments as complete factorial combination.

Table 2: Experimental treatments and used symbols/abbreviations.

Factor	Factor levels	
	common practise	adapted practise
Tillage system	conventional tillage (CT) preparation with a disc cultivator	no-till (NT) direct seeding into the previous stubbles
Seeding depth	deep: 6.5 cm	shallow: 4.5 cm
Seeding rate	high: 650 grains m^{-2}	reduced: 450 grains m^{-2}

Before installing the trial, the field was managed under CT with shallow stubble cultivation and strategic mouldboard ploughing every 4 to 7 years. Pre-sowing conventional tillage was performed with a disc cultivator at 7-8 cm. Fertilization was done as typical for the region with 70 kg N ha^{-1} as calculated after a testing for plant available soil mineral nitrogen (N_{min}) for an estimated yield of 4 t ha^{-1}. The complete amount of fertilizer was banded with the seed drill as ammonium-nitrate (‘Selitra’, 34.4 % N) directly into the seed furrow. The regional released variety Ikar was sown in all plots with a multifunctional seed drill Primera DMC (**D**irect **M**ulch **C**onventional, AMAZONEN-Werke H. Dreyer GmbH & Co. KG) with 18.75 cm row spacing and single parallelogram guided chisel openers with minimal soil disturbance. Exact seeding depth was controlled by hoop ring rollers at every individual opener. Weed regulation took place as usual on the test farm with a tank mixture of 41 g ha^{-1} Fenoxaprop-p-ethyl, 3.7 g ha^{-1} Florasulam and 205 g ha^{-1} 2,4-D, 2-ethylhexyl ester in both years. **Table 3** shows the dates of the relevant operations.

Table 3: Details of crop management for every experimental year

Parameter	Year	
	2014	2015
Previous crops	spring wheat	spring wheat
Variety	Ikar	Ikar
Seed quality	1st reproduction	2nd reproduction
Sowing date [mm.dd]	16.05	19.05
Harvest date [mm.dd]	05.09	28.08
soil N_{min}[a] [kg ha^{-1}]	32	42
Herbicide application [mm.dd]	23.06 (GS 32)	30.06 (GS 34)

[a]: 0-30 cm

Field measurements and statistics

Climate data was used from the nearby weather station at 56.10° N, 69.43° E, altitude 83 m (TUTIEMPO 2016a). Soil temperature was measured in every plot of the second block at 12.5 cm depth in 2014 and averaged as NT and CT with 4 replications. In 2015 temperature was logged in different depths (6.5 cm, 10 cm, 20 cm with 2, 4, 2 replications, respectively) in one NT and CT plot. For temperature recording we used WTDL1-Logger in 1-minute (2014) and 3-minutes (2015) intervals.

Bulk density was estimated by gravimetric measurement of 100 cm^3 undisturbed soil cores at 15 cm in the middle of the topsoil layer. Soil pH was measured in 1:2.5 0.01 M $CaCl_2$ suspension. Soil samples for N_{min} analysis were collected as mixture out of 3 points in each plot with a 30 cm auger and measured by reflectometric quick tests (Merck 2012a; Merck 2012b).

Soil volumetric water content (VWC, cm^3 cm^{-3}) was determined by time domain reflectometry (TDR) with a hand-held device (Fieldscout TDR 100, Spectrum Technologies, Inc.) at 0 to 12.5 cm before sowing and at 4 growth stages (GS11, GS31, GS65, GS75; Zadoks et al., 1974). At each GPS observation point 5 repeated measurements were taken and automatically averaged. TDR-meter accuracy for the soil texture was checked once by converting gravimetric soil moisture determinations from bulk density samples into volumetric values.

For yield determination the plots were harvested at physiological maturity (GS >90) by hand cutting of three 1 m rows within each plot. The harvested ears were oven dried at 70 °C, all yield component data are presented at 88 % dry matter. After threshing with a laboratory device (‘Minibatt’), number of grains per ear and 1000-kernel weights were determined with a ‘Contador’ seed counter (Pfeuffer). Grain crude protein content was calculated on the basis of the nitrogen content, determined according to the Kjeldahl method (European Union 2009).

All statistics were carried out in R (R Core Team 2013) using the additional package ‘agricolae’ (de Mendiburu 2014). Analyses of variance (ANOVA) were conducted according to the split-split-plot experimental design at the p=0.05 probability level. For significant effects, a Tukey HSD-post-hoc test was calculated. Comparisons between soil temperature time series were done with a t-test of the means.

RESULTS

Weather conditions

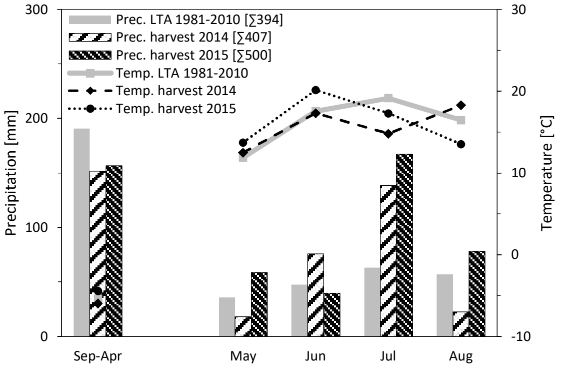

Figure 1: Climate conditions during the experimental years compared to the long-term average (LTA) as accumulated precipitation (Prec.) and average daily air temperatures (Temp.). Data source: *TUTIEMPO (2016)*Soil temperature and soil moisture

Table 4: Mean soil temperatures in different depth under no-till (NT) and conventional tillage (CT) treatment. Different letters indicate significant differences at p=0.001 probability level.

Year	Depth	NT		CT	
	[cm]	[°C]		[°C]	
2014	12.5	16.9	b	17.4	a
2015	6.5	17.8	b	18.4	a
	10.0	17.0	b	18.2	a
	20.0	16.4	b	17.5	a

During the two observed years, the weather conditions were notable different from the long-term average (**Figure 1**). Precipitation was 4 % higher in 2015 and markedly higher by 53 % in 2015 compared to the 30-year mean. Particularly July received above-average amounts of rainfall in both years. Air temperatures varied less than precipitation, but also with notable differences. Temperature sums of the growing seasons were 20 % and 8 % lower in 2014 and 2015, respectively than in the long-term mean. Therefore, the vegetation periods were one week shorter than usual with 164 and 162 days in 2014 and 2015, respectively. Due to the cold growing conditions, harvest in 2014 took place 113 days after sowing, during this time the plants received a temperature sum of 1091 GDD. In 2015, harvest was finished after 101 days with a slightly higher accumulated temperature of 1147 GDD.

Soil temperature and soil moisture

Soil temperature was significantly lower under NT compared to CT (**Table 4**). During the cold year 2014 untilled plots were in 12.5 cm depth on average 0.5 °C cooler than those with tillage. In the slightly warmer, but still above average cold year 2015 the differences were more pronounced with 0.6, 1.2 and 1.1 °C in depths of 6.5, 10 and 20 cm. Furthermore the time series showed higher amplitudes with CT (data not shown), e.g. temperature ranged in 10 cm between 10.9 – 27.7 °C with CT and only between 11.6 – 22.3 °C with NT in 2015. Seeding depth and seeding rate did not affect soil temperatures.

The soil moisture showed a significant year effect and after tillage (GS 11 to 75) significant tillage effects as well as tillage × year interactions at some growth stages (**Table 5**). Before pre-sowing tillage we found homogeneous preconditions in all plots. On average over all post-sowing measurements, VWC in 0 – 12.5 cm was by 40 % higher under NT compared to CT, which equals 5 mm. Due to the significant year differences, further statistical analysis was done for every year separately (**Table 6, Figure 2**).

After different tillage treatment, significant differences between NT and CT were observed at all measuring dates, including after several days with precipitation as well as after a period of drought. **Figure 2** shows the soil moisture as VWC in relation to the average of all variants to make the two years comparable. The differences between NT and CT were more pronounced in spring during early growth for both years. During the wetter second experimental year, differences between the tillage systems were less pronounced than in 2014. Little impact of preceding precipitation could be seen in the comparison of the two last observations with opposite rainfall directions but similar soil moisture patterns.

Table 5: ANOVA for Volumetric Water Content in 0-12.5 cm. GS: growth stage. * p<0.05, ** p<0.01, *** p<0.001.

Factor	GS 0	GS 11	GS 31	GS 65	GS 75
Tillage (T)	0.057 .	<0.001 ***	<0.001 ***	<0.001 ***	<0.001 ***
Seeding depth (D)	0.524	0.202	0.528	0.050 .	0.412
Seeding rate (R)	0.837	0.246	0.136	0.988	0.265
Year (Y)	<0.001 ***	<0.001 ***	0.006 **	<0.001 ***	<0.001 ***
T × D	0.803	0.888	0.008 **	0.925	0.914
T × R	0.207	0.781	0.777	0.194	0.078 .
D × R	0.749	0.272	0.419	0.714	0.322
T × Y	0.028 *	0.522	<0.001 ***	0.002 **	0.001 ***
D × Y	0.609	0.012 *	0.687	0.796	0.782
R × Y	0.919	0.564	0.273	0.488	0.168
T × D × R	0.819	0.403	0.841	0.471	0.164
T × D × Y	0.859	0.878	0.623	0.420	0.855
T × R × Y	0.566	0.900	0.118	0.152	0.104
D × R × Y	0.635	0.686	0.488	0.429	0.544
T × D × R × Y	0.015 *	0.222	0.852	0.512	0.533

Table 6: Mean volumetric water content for all variants at 4 different growth stages (GS) for each year including results of post-hoc HSD-Test (different letters indicate significant differences at p=0.05). NT: no till, CT: conventional tillage, ↓: 6.5 cm seeding depth: ↑ 4.5 cm seeding depth, 600/450: seeding rate (grains m^{-2})

Year	Treatment	Before sowing	GS 11	GS 31	GS 65	GS 75
2014	NT↓600	21.41 a	23.46 a	20.74 a	27.32 a	16.78 ab
	NT↓450	21.76 a	25.07 a	22.47 a	29.06 a	20.93 a
	NT↑600	24.19 a	25.06 a	19.18 a	29.24 a	18.64 a
	NT↑450	20.81 a	22.20 a	21.33 a	31.21 a	19.66 a
	CT↓600	21.95 a	12.55 b	10.45 b	18.48 b	11.67 c
	CT↓450	20.96 a	12.08 b	10.89 b	18.72 b	11.08 c
	CT↑600	21.24 a	12.81 b	11.54 b	20.51 b	12.21 bc
	CT↑450	24.41 a	13.04 b	11.74 b	18.03 b	11.99 bc
	HSD$_{0.05}$	7.43	5.89	4.53	4.76	5.08
2015	NT↓600	32.12 a	25.42 a	20.57 a	38.71 a	37.18 ab
	NT↓450	30.47 a	24.43 a	19.52 ab	37.99 a	37.63 a
	NT↑600	31.48 a	28.47 a	19.33 ab	39.33 a	38.38 a
	NT↑450	32.00 a	27.09 a	19.60 ab	39.14 a	37.81 a
	CT↓600	26.89 a	14.12 b	14.37 c	31.72 b	33.54 c
	CT↓450	29.51 a	13.81 b	14.47 c	31.22 b	33.19 c
	CT↑600	29.50 a	18.52 b	14.62 c	32.79 b	34.18 bc
	CT↑450	27.71 a	16.84 b	16.01 bc	32.68 b	34.17 bc
	HSD$_{0.05}$	5.85	5.81	4.04	3.21	3.40

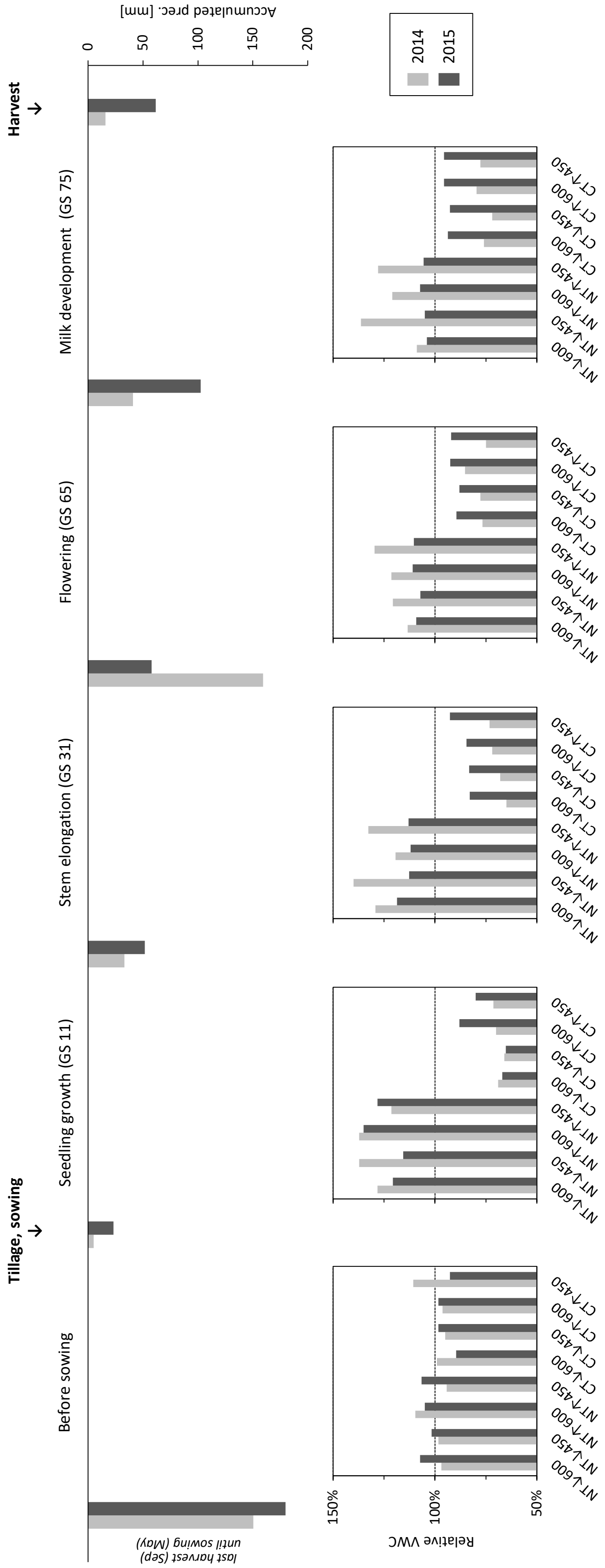

Figure 2: Relative volumetric water content of each variant compared to the mean of all variants at every growth stage (GS). NT: no till, CT: conventional tillage, ↓: 6.5 cm seeding depth: ↑ 4.5 cm seeding depth, 600/450: seeding rate (grains m^{-2})

Yield

Grain yield and all individual yield components showed a significant year effect. All yield forming parameters further had a significant response on seeding rate, while thousand-kernel weight (TKW) also significantly responded to seeding depth (**Table 7**). There were some more significant interactions, mostly with year, therefore the years were analysed separately.

Mean grain yield was higher with 3.28 t ha^{-1} in 2015 than 2.75 t ha^{-1} in 2014. The higher yield in 2015 was built by heavier grains (42 g TKW compared to 34 g in 2014) and larger ears (24 grains ear^{-1} compared to 17 in 2014) but with lower stand densities (327 ears m^{-2} compared to 487 in 2014). Higher grain yields were observed in both years in NT treatments with significant differences to the lowest yield under CT treatment (**Table 8**). In 2014, the high number of ears m^{-2} was homogeneously found in all treatments, whereas the two remaining yield components showed a response, the number of grains ear^{-1} according to seeding rate and TKW were without a clear pattern. In 2015, the low number of ears m^{-2} showed a response to seeding rate and the two other yield building factors had uniform high values.

Grain protein content was on average similar in both years (108.7 and 107.1 g kg^{-1}) with no differences between the treatments in 2014 and one significant difference between shallow and deep placed seeds under NT with high seeding rate in 2015.

Table 7: P-values from ANOVA for yield components. TKW: Thousand-kernel weight. * $p<0.05$, ** $p<0.01$, *** $p<0.001$.

Factor	Grain yield	Protein	Ears m^{-2}	Grains ear^{-1}	TKW
Tillage (T)	0.091 .	0.744	0.079 .	0.960	0.588
Seeding depth (D)	0.081 .	0.033 *	0.575	0.069 .	0.002 **
Seeding rate (R)	0.263	0.625	<0.001 ***	<0.001 ***	0.050 *
Year (Y)	<0.001 ***	0.149	<0.001 ***	<0.001 ***	<0.001 ***
T × D	0.044 *	0.639	0.238	0.211	0.640
T × R	0.681	0.063 .	0.958	0.843	0.065 .
D × R	0.846	0.033 *	0.724	0.541	0.991
T × Y	0.070 .	0.007 **	0.005 **	0.170	0.023 *
D × Y	0.987	0.573	0.905	0.700	0.852
R × Y	0.162	0.735	0.353	0.323	0.263
T × D × R	0.968	0.910	0.837	0.787	0.272
T × D × Y	0.390	0.098 .	0.804	0.495	0.491
T × R × Y	0.053 .	0.524	0.697	0.282	0.065 .
D × R × Y	0.747	0.220	0.876	0.870	0.806
T × D × R × Y	0.160	0.149	0.780	0.229	0.458

Table 8: Yield and yield components. Different letters indicate significant differences (Tukey-HSD test, p=0.05). NT: no till, CT: conventional tillage, ↓: 6.5 cm seeding depth: ↑ 4.5 cm seeding depth, 600/450: seeding rate (grains m^{-2}), TKW: Thousand-kernel weight.

Year	Treatment	Grain yield	Protein	Ears m^{-2}	Grains ear^{-1}	TKW
		t ha^{-1}	g kg^{-1}			g
2014	NT↓600	3.19 a	112.00 a	527.41 a	17.55 abc	34.54 a
	NT↓450	2.77 ab	110.33 a	437.93 a	19.23 a	33.67 ab
	NT↑600	2.72 ab	111.67 a	533.93 a	15.67 abc	33.13 ab
	NT↑450	2.71 ab	108.67 a	443.85 a	19.07 ab	32.21 b
	CT↓600	2.31 b	108.00 a	505.78 a	14.06 c	32.67 ab
	CT↓450	2.69 ab	105.67 a	436.15 a	17.97 abc	33.93 ab
	CT↑600	2.70 ab	105.00 a	550.52 a	15.08 bc	32.66 ab
	CT↑450	2.88 ab	108.33 a	456.89 a	18.82 ab	34.31 a
	HSD$_{0.05}$	0.65	12.47	128.01	4.11	2.10
2015	NT↓600	3.77 a	113.00 a	391.11 a	23.79 a	40.57 a
	NT↓450	3.82 a	104.67 ab	336.59 abc	26.94 a	42.19 a
	NT↑600	3.48 ab	101.67 b	391.70 a	22.22 a	40.10 a
	NT↑450	3.23 ab	104.00 ab	330.67 abc	24.33 a	40.43 a
	CT↓600	3.03 ab	107.00 ab	306.96 abc	23.31 a	42.24 a
	CT↓450	2.48 b	107.33 ab	240.00 c	24.09 a	42.71 a
	CT↑600	3.37 ab	107.00 ab	344.30 ab	23.57 a	41.38 a
	CT↑450	3.08 ab	112.00 ab	274.37 bc	26.29 a	42.86 a
	HSD$_{0.05}$	1.20	11.17	96.83	5.51	3.69

Figure 3 shows the averaged results from both years in relation to the mean over all treatments for each year. The grain yield was highest in deep sown NT plots and lowest in deep sown CT plots, without significant effects of seeding rate. The significant tillage × seeding depth interaction is visible, as higher yields in NT were observed with deep placement and in CT with shallow seeding depth. Protein content was on the same level in both years as well as among all treatments. Seeding rate affected the two yield components ears m^{-2} and grains ear^{-1} in opposite directions: plots with higher seeding rates built their yield predominantly by the number of ears and plots with lower seeding rate by more grains in each ear (**Figure 3**C, D). TKW was yield determining in CT plots with low seeding rates and low grain yields. Seeding rates led to significantly different stand densities and ear weights, but these opposite effects were mostly compensated in terms of grain yield, since there were never significant differences for seeding rates within the same tillage × seeding depth treatment.

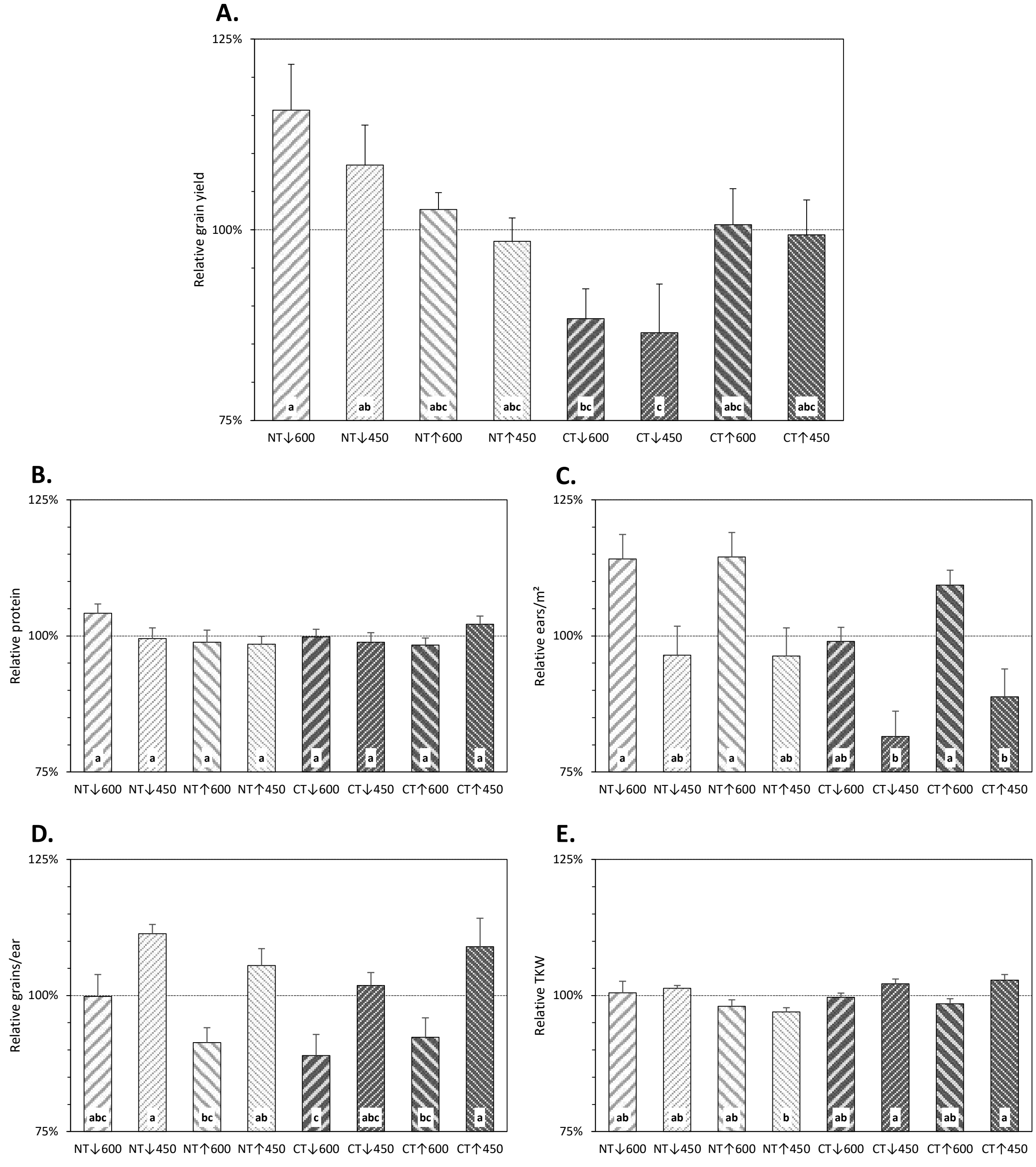

Figure 3: Average values from both years in relation to the mean of all treatments for grain yield (A.), grain protein content (B.), number of ears m^{-2} (C.), number of grains ear^{-1} (D.) and thousand-kernel weight (TKW, E.). Different letters indicate significant differences (Tukey HSD-test, p=0.05). NT: no till, CT: conventional tillage, ↓: 6.5 cm seeding depth: ↑ 4.5 cm seeding depth, 600/450: seeding rate (grains m^{-2})

Weed infestation

Herbicide management in this trial was not integrated as factor in the experimental design, therefore the herbicide application was the same in all plots. In general, weed infestation during early growth (before herbicide application) was the same, but with differences in the weed communities between the tillage treatments. In NT plots mainly perennial, dicotyledonous weeds developed and in CT plots predominantly annual species were observed. Most frequent we found *Amaranthus retroflexus, Conyza canadensis, Artemisia vulgaris, Fallopia convolvulus, Avena fatua, Galeopsis tetrahit*. After herbicide application, there was no difference between the tillage treatments.

DISCUSSION

During the 2-year field trial some differences in soil moisture and yield components were observed, but NT as part of conservation agriculture needs a transition period of 3 to 7 years, until soil structure and conditions change into the new system (Känkänen et al. 2011; Derpsch et al. 2014).

Soil physical properties

Although the observed years received above-average amounts of rainfall, soil moisture was significantly higher in NT plots during the entire growing seasons. A close link between increased SWC and stubble height was reported from trials in the Canadian prairie with highest effects after direct seeding into tall (>30 cm) stubbles (Cutforth and McConkey 1997). In our trial the stubbles were higher in 2015, since harvest in autumn 2014 had to be done quickly due to early snow the combine was working fast. The taller stubbles could explain higher initial soil moisture because of more efficient snow trapping in addition to a slightly higher amount of snowfall during the second winter. The importance of snow trapping by previous stubbles in NT systems was also mentioned by Sainju et al. (2009). Stubbles help to recharge the soil water storage during snowmelt, whereas later during the growing season, the mulch cover is most important. Higher losses of SWC in CT could be explained by more evaporation from the bare soil after tillage treatment together with the darker colour and less isolation because of missing mulch cover (Kabakci et al. 1993). Similar differences in soil moisture between CT and NT treatments were observed in semi-arid wheat production by Gozubuyuk et al. (2015). The differences in precipitation use efficiency are more pronounced in drier climate. Our trial took place in two wet and cold years, but reduced evaporation losses and therefore better water-use efficiency of NT spring wheat is mentioned by Sainju et al. (2009) especially for smaller amounts of precipitation. (Kabakci et al. 1993) stated that the primarily water supply from stored soil moisture causes a wheat root development following the receding water profile downward. In consequence, the active surfaces of the roots are not in the vicinity of light summer precipitation on the soil surface and therefore evaporation losses prevail (Kabakci et al. 1993). That is why particularly in poor crop years a good residue management helps to optimise SWC and thereafter grain yield. Since climate change scenarios predict rising temperatures and insignificant precipitation changes for Western Siberian grain belt (Degefie et al. 2014), NT benefits for soil moisture are likely to become greater.

Besides precipitation and the resulting soil water storage also small differences in temperature sums may significantly affect grain yields (Qi et al. 2013), which is in line with our above-average cold year 2014 that resulted in overall lower yield than 2015. By contrast, the reduced soil temperatures can also cause adverse effects: topsoil without tillage remains wet and cold longer in spring than tilled soils and may delay early crop development (Känkänen et al. 2011). This phenomenon was not observed in our trial, there were only one to two days delay in emergence, but between deep and shallow seed placement and not with respect to tillage. In general, spring is short in Siberia (Suleimenov 2006) and if the soil moisture allows driving on the field with heavy machinery, soil temperature is already above 14 °C in the topsoil layer.

Other reported effects on soil physical properties like redistribution of pore sizes from medium to capillary and macro with consequences of infiltration and deep drainage (Fernández-Ugalde et al. 2009; Gozubuyuk et al. 2014) were not visible in the first years of NT in our study but are likely to develop under continuous management without tillage.

Tillage effects

From global meta-analyses we know that NT can result in higher yields, in dry environments and for cereals

(Pittelkow et al. 2015) with largest effects of yield enhancement by 7.3 % if NT is implemented in the system of CA (Pittelkow et al. 2014). In individual studies, e.g. Lafond et al. (2006) found no adverse effects of NT systems in the Canadian prairies, an environment comparable to Western Siberia. The relation of equal or even better yields with NT compared to CT are explained by the importance of SWC in dryland agro-ecosystems (Nielsen et al. 2002). Qi et al.(2013) simulated, that only 42 % of the potential water need was available for dryland spring wheat in China to emphasise the importance of water saving strategies. Lenssen et al. (2014) observed, however, in the northern Great Plains different effects of tillage treatment on yield and yield components, in years with no limitation in soil water, CT yielded more but in drought years NT yields were higher.

Our cold and wet condition resulted in statistically equal yields in both tillage treatments, but the overall best factor combination was with NT and the poorest with CT treatment. The observed average yields from 2.75 and 3.28 t ha^{-1} in 2014 and 2015, respectively were slightly lower than potential yields for the used variety 'Ikar' from 3.22 up to 5.55 t ha^{-1}, estimated in demonstration trials from 2003 to 2007 by Sapega and Tursumbekova (2010). Whilst the TKW from 2015 (42 g) was within the typical range for Siberian varieties of 40 to 50 g (Gamzikov and Nosov 2010), the grains from 2014 were significant smaller (34 g). Furthermore, notable higher protein contents (150 to 180 g kg^{-1}) are possible in Siberia under average climate conditions compared to our poor yield quality with 109 and 107 g kg^{-1} (Gamzikov and Nosov 2010).

Poor field emergence in NT treatment due to lower soil temperatures during early growth was mentioned as a disadvantage of direct seeding by Känkänen et al. (2011). There was no significant effect of tillage on field emergence, but the stand densities always seemed influenced by seeding rates.

Seeding rates

In general, typical Siberian seeding rates are much higher than those in comparable dryland areas like the northern Great Plains. For our study region – Ishim in Tyumen province – official recommendation for conventional spring wheat cultivation was 6 million plants ha^{-1} (Ministry of Agriculture in Tyumen region 2015). Reasons for such high seeding rates are late sowing dates in the second half of May (Qi et al. 2013) as well as limited potential of the regional released varieties. Since seed reproduction is normal for most farms, germination rates are much lower than for quality seeds, in particular if the seeds are stored under semi optimal conditions over winter. This led to comparable high seeding rates of 240 kg ha^{-1} for the usual variant and 180 kg ha^{-1} for the variant reduced by 25 %. Considerable lower seeding rates were reported for NT from the northern Great Plains with 60 to 135 kg ha^{-1} (Lafond et al. 1991; Lafond 1994; Cutforth and McConkey 1997; Campbell et al. 2004; Lafond et al. 2006; Sainju et al. 2009), from semi-arid north west Victoria, Australia with 60 to 100 kg ha^{-1} (O'Leary and Connor 1997). However, without the information about stand densities these values are not comparable. Some insights on the better seed quality were given by Kabakci et al. (1993) with the combined information of seeding rate by 100 kg ha^{-1} for 555 to 605 tillers m^{-2} from a trial in Washington, USA. Additionally, an older study from Faris and De Pauw (1980) mentioned both, 80 to 180 kg ha^{-1} for 300 to 675 seeds m^{-2}. Better comparable seeding rates, expressed in grains m^{-2}, were reported form NT trials in the northern Great Plains with 250 to 320 seeds m^{-2} (Halvorson et al. 2000; Miller et al. 2002; Krupinsky et al. 2006), from the Loess Plateau in China with 371 to 395 seeds m^{-2} (Qi et al. 2013), and from Finland with 620 to 675 seeds m^{-2} (Känkänen et al. 2011). Grunwald et al. (2015) conducted demonstration trials with substantial lower rates of 268 to 336 seeds m^{-2} in Altai krai, Western Siberia that resulted in higher yields than our trial. In Russia, breeding for new varieties is still managed by state institutes and universities or academies (Suleimenov et al. 2010) and local adapted, high performing varieties from international companies are not available, in particular for Siberia. The limited potential of the typical varieties for Tyumen region may help to explain the high seeding rate recommendations. Nevertheless, Sapega and Tursumbekova (2010) reported yield stability for the used variety under variable weather conditions in the study areas.

Interestingly, we found a different yield component response on seeding rate between the two investigated years. Under cold conditions in 2014, stand densities were homogeneous and differences occurred in the number of grains ear^{-1}. Under wet conditions in 2015, stand densities developed different with homogeneous ears. Under predominantly post-anthesis temperature limitations (2014) the overall smaller yield was built from higher stand densities with fewer ears and smaller grains. With greater water supply and slightly above-average pre-anthesis temperatures (2015) larger ears with heavier grains and low stand densities with a pattern that followed the seeding rates built the higher yield. Because of this opposite directions, it is hard to conclude what would happen under drier conditions. Grunwald et al. (2015) stated a clear single plant strategy for yield optimisation of their local seeds. From tests in Canada, however, a significant seeding rate × variety interaction was reported by Faris and De Pauw (1980).

Regardless of the optimal rates, higher seeding rates for NT compared to CT are usual as well as higher rates with later sowing date, which is usual in Siberia due to late traficability (e.g. Känkänen et al., 2011; Lafond, 1994; Qi et al., 2013). For the wetter areas of the northern Great Plains, higher seeding rates were recommended for NT, because of the low potential to compensate delayed early development in short season spring wheat production (Lafond 1994). With nearly 400 mm mean annual precipitation, our study area is comparable with the wetter north of the Great Plains and may need higher seeding rates. Nevertheless, this tillage × seeding rate interaction was not observed in our trial. Maybe our reduction of the seeding rate by 25 % was too small for clear differences as other studies reduced up to 75 % (Tompkins et al. 1991).

Potential of NT for Western Siberia

The central aim of adaptation strategies to climate change effects of Siberian cropping systems are not higher yields in average years but stable yields in extreme years. The possibility to ensure constant yield by a complete adoption of the CA system including NT, diverse crop rotation and residue soil was reported from the semi-arid western Loess Plateau, China by Huang et al. (2008).

Besides yield stability, NT provides further benefits like energy savings and erosion protection. Erosion is known to be a large problem in the study area (Gabbasova et al. 2015). In particular, snow melt erosion contributes to a large amount to loss of soil fertility (Tanasienko et al. 2011; Yakutina et al. 2015), which could be reduced by more homogenous snow trapping in tall stubbles. CA has moreover the potential to sequester carbon within the soil. Gaston et al. (1993) estimated an area suitable for NT of 181 million ha across the Former Soviet Union. This area, they calculated, has the potential to sequester 3.3 Gt of carbon during the first 10 years after conversion from CT to NT. From a meta-analysis about agricultural soils across the temperate zone, Kämpf et al. (2016b) identified significant higher soil organic matter stocks when NT was practised. Powlson et al. (2014) stated, however, that most of these calculations overestimate the carbon sequestration potential of NT due to a redistribution within the soil profile and/or lack of exact paired data.

In the long term, also some adverse environmental effects like increased use of herbicides or the development of herbicide resistant weeds are related to NT (Hobbs et al. 2008). From some spraying windows within the trial, we found significantly higher weed infestation without herbicide application on our experimental field (Kämpf et al. 2016a). Following our experimental design, the weed management strategy was the same in both tillage systems, but additional pre-sowing spraying with glyphosate is common practice (Nichols et al. 2015). Similar changes in weed species composition as we observed were documented from a study in Novosibirsk, Western Siberia (Korotkikh and Vlasenko 2014): In their study, after conversion from CT to NT less weeds germinated, but vegetative growth of survived weed plants was a problem. Differences in soil temperature may have caused the increased abundance of *Amaranthus retroflexus* under NT (Korotkikh and Vlasenko 2014). The same pattern of less individuals, but heavier species were determined by Vlasenko et al. (2013) concluding the importance of appropriate crop rotations when performing NT. The necessity of an integrated management system with diverse crop rotations was also emphasised by Lenssen et al. (2014) and O'Donovan et al. (2007) to avoid the development of herbicide-resistant weed populations like known from the northern Great Plains. Given the good praxis of integrated weed management, large-scale farms in Western Siberia are already equipped with spraying technology and may therefore adapt the CA system easier than smallholder farmers of dryland areas elsewhere (Serraj and Siddique 2012; Giller et al. 2015). A few kilometres further south in the northern Kazakh steppe CA is already well adapted and likely to further expand during the next years (Kienzler et al. 2012).

Looking on the entire dryland cropping system, NT enables due to the potential of increased SWC the substitution of summer fallow by continuous cropping (e.g. Arshad et al., 2002; Lenssen et al., 2014; Miller et al., 2002; Sainju et al., 2009). Particularly when focussing on spring wheat as a high water use crop, the rotation is of importance in semi-arid environments (Lenssen et al. 2014). Results from several long-term studies revealed that diverse rotations with continuous cropping including oilseed rape or pulses like pea were advantageous against fallow-based sequences. Yearly average of biomass production, grain yields and economic benefits were higher compared to traditional systems (Hansen et al. 2012). From trials in Northern Kazakhstan, Suleimenov et al. (2010, 2005) came to the same conclusion, with agronomical best results for fallow substitution by oats and high potential for pulses under an economic perspective. Further development of the Western Siberian cropping systems, particularly in conjunction with climate change impacts, could be based on the integration of winter crops.

An increase of water stress and more frequent droughts are predicted to affect future crop production in Western Siberia (Alcamo et al. 2007; Degefie et al. 2014). Spring wheat was found to use water more efficiently under NT especially during drought years (Lenssen et al. 2014) under comparable agro-climatic conditions (Morgounov et al. 2010). There is still an ongoing debate about the predicted net effect of climate change on crop production in Siberia if not only temperature and precipitation changes but also elevated CO_2 levels have to be taken into account (White et al. 2011). Maracchi et al. (2005) estimated the potential for compensation of heat stress by elevated CO_2 for high latitude regions. Positive impacts of climate change for spring wheat production in north of Kazakhstan were also reported from modelling simulations by Sommer et al. (2013) with possible changes in grain yields of +15 % or 0.32 t ha^{-1}. Higher temperatures may lead to earlier and faster crop growth in spring and together with the fertilization effect of elevated CO_2 levels contribute to beneficial effects, in particular for winter cereals.

CONCLUSION

We found in two above-average wet and cold growing seasons significant better soil water storage of NT and no adverse effect on spring wheat grain yield and quality for the study site in the south of Western Siberia. The regional Russian spring wheat variety was able to compensate seeding rate variations by opposite manifestation of the individual yield components. The common deep seed placement was found to be beneficial for NT but shallow placement was advantageous with CT. Predicted rising temperature stress and increased climate variability require more resilient cropping systems in future, in particular in dryland agriculture. Against this background, NT practice could be one contribution to sustainable land management in Western Siberia, if it is implemented as part of conservation agriculture and based on residue management and diverse crop rotations.

ACKNOWLEDGEMENTS

The field trial was conducted as part of project SASCHA (‘Sustainable land management and adaptation strategies to climate change for the Western Siberian grain belt’). We are grateful for funding by the German Government, Federal Ministry of Education and Research within their Sustainable Land Management funding framework (funding reference 01LL0906D). We thank S. Nülle, M.Bokelmann, J. Kampschulte J. Nickel for help with the field work and V. Buxmann and A. Krasnoborov for machinery support as well as M. and S. Mamontov for providing the test site. Finally, we acknowledge the valuable comments of two anonymous reviewers.

PICTURE CREDIT

Insa Kühling

Fertilizer types and levels, 26 May 2015

2.4 Potential of a new slow-release urea fertilizer under on-farm conditions in a semi-arid environment [IJERD 7-1 (2016) 44-49]

AUTHOR CONTRIBUTIONS

Insa Kühling developed the experimental design and monitoring programme, installed the field trial, analysed all data, conducted the statistics and wrote the manuscript
Dmitry Redozubov produced the fertilizer and conducted the field trial, performed the post-harvest analysis and contributed a literature overview to the introduction chapter
Christian Jeismann helped with the field work, analysed the soil samples reflectometric and performed the SPAD measurements in the field
Igor Komissarov invented the fertilizer production and supervised Dmitry Redozubov
Dieter Trautz contributed to the development of the experimental design and supervised Insa Kühling

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International Journal of Environmental and Rural Development 7-1 (2016) 44-49

POTENTIAL OF A NEW SLOW-RELEASE UREA FERTILIZER UNDER ON-FARM CONDITIONS IN A SEMI-ARID ENVIRONMENT

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Submitted
6 January 2016
Accepted
11 April 2016

Keywords
slow-release fertilizer, silicate coating, urease inhibitor, Nitrogen use efficiency, spring wheat, Western Siberia

ABSTRACT

Nitrogen (N) fertilizers play an important role to increase grain yield and grain quality in crop production systems. In Western Siberia, predominantly used N-fertilizers for cereal production are urea and ammonium-nitrate (‘Selitra’). Due to semi-arid climate, only one fertilizer application is common, simultaneously with sowing and directly into the seed furrow. A new kind of slow-release fertilizer is a modified urea with silicate coating and urease inhibitor and was developed at the State Agrarian University of the Northern Transurals (Russian Federation). In a field trial, the comparative performance of the novel fertilizer type was tested with spring wheat near the city of Ishim in Tyumen region (Western Siberia) on 3.4 ha under on-farm conditions. 4 levels of the slow-release urea (25/50/75/100 %) were compared to 100 % of conventional urea, 100 % of Selitra and an unfertilized control in randomized complete block design with 4 replications. Results showed significant differences in soil nitrate availability but no differences in ammonium release. Differences between N-levels dispersed during heading, afterwards only plots with Selitra fertilization showed significant higher nitrate values. Leaf chlorophyll content as indicator for plant Nitrogen supply showed significant differences from beginning stem elongation on. The harvested grain yield showed no significant differences between the compared fertilizer types at the 100 % N-level. Even if the grain yield with reduced dose of slow-release fertilizer was on the same level, it was not significantly higher than the unfertilized control. From the results of this field trial there seems to be no beneficial advantage of the tested slow-release fertilizer so far.

INTRODUCTION

Nitrogen (N) fertilizers play an important role to increase wheat productivity and grain protein content. In Western Siberia predominantly ammonium-nitrate (‘Selitra’) and urea are used for N-fertilization. Due to the dry sub-humid climate (Selezneva 1973), only one N-application is common, simultaneously during sowing.

Also from an economic point of view, N-fertilizers play a key role in grain production processes and due to high inputs of energy, they mainly affect the total economic balance (Lubkowski 2014).

Urea is the most used Nitrogen fertilizer around the world agriculture, because of the high Nitrogen content by 46.6 % (Trenkel 1997; Zheng et al. 2009). When urea is applied to a soil, it is almost immediately hydrolysed into ammonium carbonate, which breaks down to carbon dioxide (CO_2) and ammonia (NH_3), producing high soil pH and ammonia loss (Fenn and Kissel 1973; Eriksen and Kjeldby 1987). The remainder of the ammonium in the soil can be converted to nitrates by the soil bacteria. Therefore, reducing water solubility of urea granules by physical or chemical inhibitors is very important and can improve the Nitrogen use efficiency (NUE) by preventing or slowing down these processes.

Such types of modified fertilizers are described as ‘enhanced efficiency fertilizers’ which are able to reduce the risk of nutrient losses to the environment, retain nutrients in less leachable forms, reduce solubility and maintain nutrients in the root zone by physical barriers (coating) (Trenkel 2010). Furthermore, three different subtypes are characterised: (1) Stabilised fertilizers have a chemical inhibitor to slow down the hydrolysis of urea with further transformation to NH_4^+ and inhibitors to stop the oxidation of ammonium (NH_4^+) to nitrate (NO_3^-); (2) Slow-release fertilizers are less-soluble and N is initially not plant available but needs to be converted into plant available N forms; (3) Controlled-release fertilizers are quick soluble fertilizers with a coating of hardly soluble material with a predictable rate of Nitrogen release when used at the manufacturer specified temperature (Trenkel 1997; Trenkel 2010).

Prognoses for the development of the fertilizer industry predict an increase until 2020 to 1.9 – 2.2 million tons of slow- and controlled-release fertilizer products. One of the drawbacks, particularly for the currently most widespread polymer-coating, is the remaining amount of useless polymer that is left in the soil after nutrient consumption (Trenkel 2010). A perspective alternative - although not yet used on a technological scale - is to produce slow-release fertilizers by using Calcium Silicate ($CaSiO_3$) as a mineral coating material, which can easily be decomposed by silicate bacteria to environmentally friendly inorganic elements. The new type of such a slow-release urea fertilizer was developed at the State Agrarian University of the Northern Transurals (Russian Federation). A combination of a physical barrier by $CaSiO_3$-coating and a chemical urease inhibitor was chosen to delay the release of plant available Nitrogen.

The objective of this study was to compare the performance of the novel slow-release urea fertilizer against common practice and to evaluate the potential for improving the Nitrogen use efficiency under practical conditions.

METHODOLOGY

Study area

We installed a 3.4 ha field trial with spring wheat in Ishim (Tyumen province, Russia, **Figure 1**) in RCBD with 4 replications to compare 4 levels of coated urea ‘CU’ (100/75/50/25 %) against 100 % of conventional uncoated urea ‘UU’, 100 % of Selitra ‘S’ and a unfertilized control ‘C’. 100 % equals 70 kg ha^{-1} N (**Table 1**). The fertilizer was applied directly into the seed furrow. The seed rate was constant over all variants by 240 kg ha^{-1} for 600 plants per m^2. The plots were sown with the regional variety ‘Ikarus‘ on May 19th, harvest took place on September 28th, weed regulation was done only once as usual for the region.

Table 1: Investigated variants with amounts of fertilizer and Nitrogen applied

variant		fertilizer type	N level [%]	applied fertilizer [kg ha^{-1}]	applied Nitrogen [kg ha^{-1}]
Control	⬜	no	0	0	0.0
S100	🟨	Selitra	100	203	70.0
UU100	🟩	uncoated urea	100	150	70.0
CU100	🟫	coated urea	100	153	70.0
CU75	🟧	coated urea	75	115	52.2
CU50	🟧	coated urea	50	77	35.0
CU25	⬜	coated urea	25	38	17.5

Fertilizer production

The fertilizer was produced on the laboratory scale by ’Биотех‘ at the State Agrarian University of the Northern Transurals. Liquid Na_2SiO_3 was poured over usual urea in the first step. Secondly, liquid $CaCl_2$ was added which induced the drying process. Finally, urease inhibitor was applied on the coating. The coating material was between 1 and 3 % of the total mass of the fertilizer granules.

Analyses and statistics

Soil N_{min} (NO_3 + NH_4) analysis for 0-30 cm was done reflectometric (Merck) and for determination of leaf chlorophyll content a SPAD-502 (Minolta) was used at the youngest fully developed leaf. Comparisons among means were carried out in R using the package agricolae (LSD-Test, p<0.05) (R Core Team 2013). Between values with the same letter, there is no significant difference.

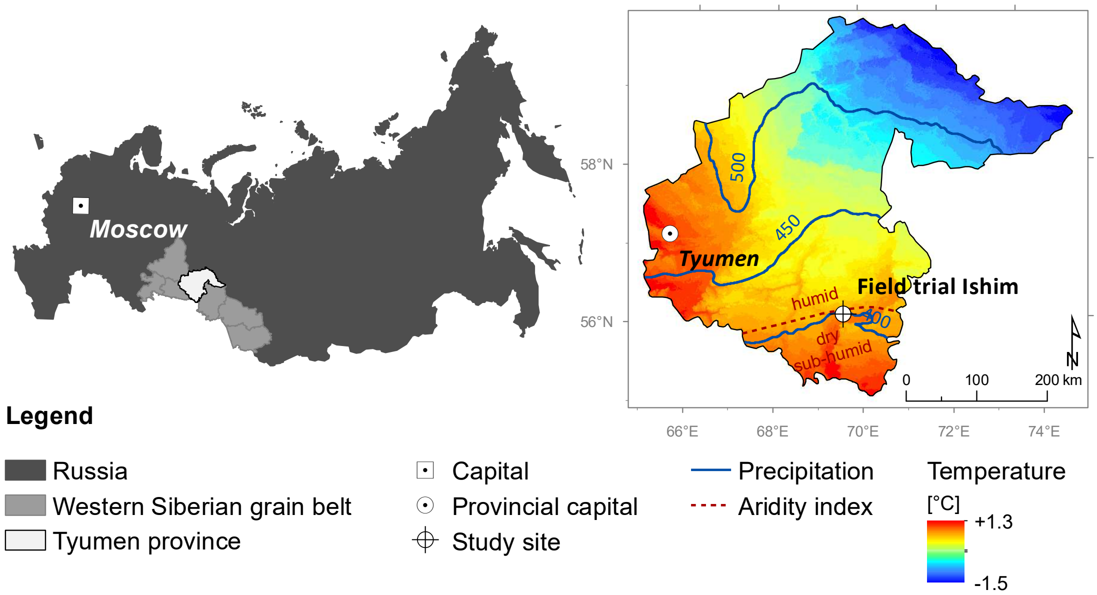

Figure 1 Location and mean annual agro-climatic conditions of the study area.
Souces: CGIAR-CSI (2009), GADM (2012), WorldClim (2013).

RESULTS AND DISCUSSION

Soil Nitrogen

The results of soil analysis showed significant differences in nitrate content but no significant differences in ammonium content (**Figure 2**). Homogeneous preconditions were given by a constant level of both N_{min} fractions before fertilization. During leaf development, the variants Nitrogen availability differentiated, but only between the fertilizer types and not among the CU variants. Later in the growing season, only the S100 plots showed significant higher NO_3 content in the soil.

Even if there were no significant differences between soil ammonium contents, due to the differences in nitrate levels, a closer look on the proportions was necessary. **Table 2** shows significant differences in the ammonium share, starting during leaf development, where values in unfertilized control plots were highest. This trend of low NH_4 proportion in conjunction with high nitrate content continued until the last measurement.

Leaf Nitrogen

The SPAD-meter readings of the leaf-chlorophyll content are known to be a good indicator for leaf Nitrogen content (Markwell et al. 1995; Uddling et al. 2007). The results showed a plausible response according to the N-level since beginning of stem elongation (**Figure 3**). Reduced N levels resulted after heading in significant lower leaf chlorophyll contents.

Yield results and N balance

The harvest results confirmed the observed soil and plant parameters, as there were no significant differences between the 100 % variants of the three fertilizer types for all yield parameters (**Table 3**). The only significant differences occurred between unfertilized control and 75-100 % fertilized plots for grain yield and the number of grains per ear.

All fertilizer types at 100 % N-level resulted in comparable grain yields, among protein contents there were no differences at all (**Figure 4**).

The last step was to balance the Nitrogen inputs and outputs for all variants and to calculate the N use efficiency (NUE=N uptake/fertilizer N). **Table 4** shows a slight advantage for UU100 with an optimal NUE of 1.0, but also S100 and CU100 were on a good level. Higher NUE above 1.0 leads to unsustainable soil mining and should be avoided.

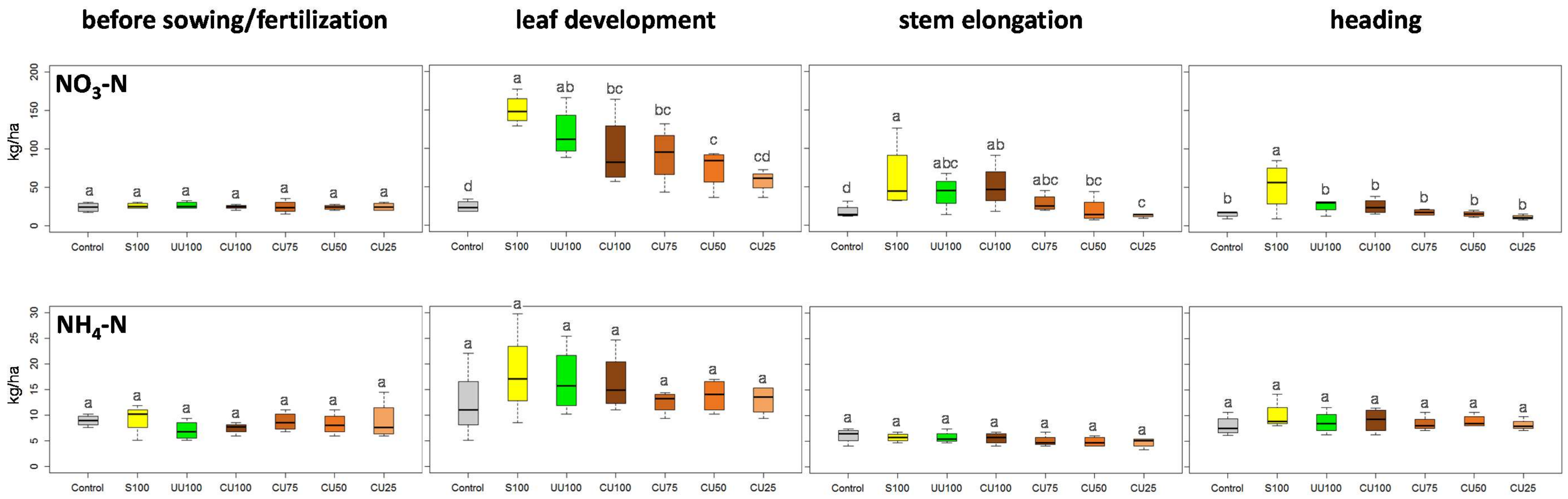

Figure 2: Soil N_{min} components NO3-N and NH4-N in 0-30 cm before sowing/fertilization and at 3 development stages.
Boxes show lower and upper quartiles, black line depicts the median, whiskers between min and max.

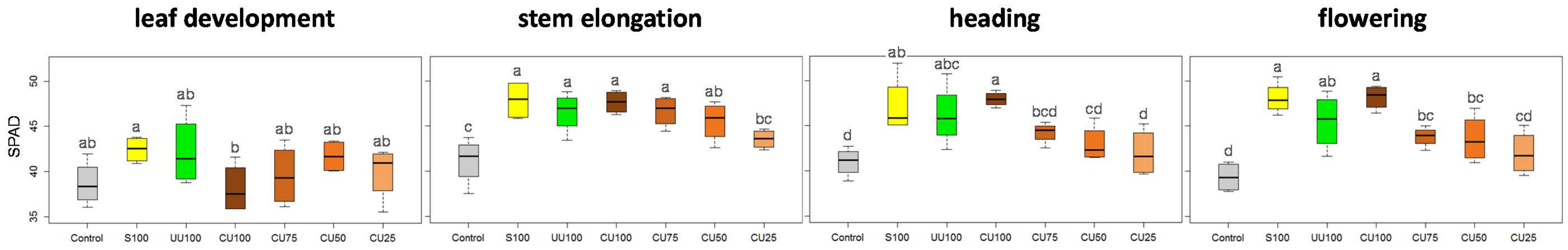

Figure 3: SPAD-meter readings at 4 development stages.
Boxes show lower and upper quartiles, black line depicts the median, whiskers between min and max.

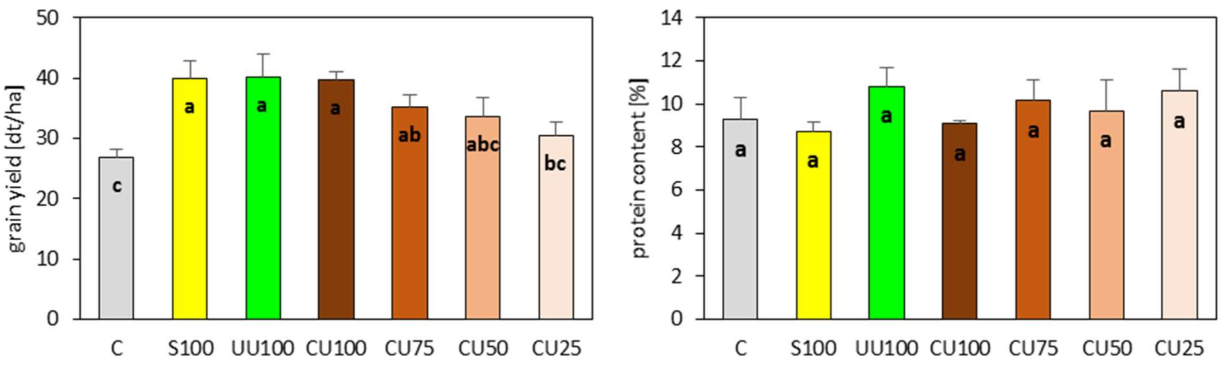

Figure 4: Harvest results for grain yield (left) and protein content (right).Error bars show 1 standard error of the mean.

Table 2: NH_4-N proportion of total N_{min} (0-30 cm) at 3 sampling dates for all variants

development stage	Control	S100	UU100	CU100	CU75	CU50	CU25
before sowing/fertilization	28 % a	27 % a	21 % a	23 % a	27 % a	26 % a	26 % a
leaf development	32 % a	10 % b	12 % b	15 % b	14 % b	17 % b	19 % b
stem elongation	27 % a	11 % c	15 % bc	13 % c	16 % abc	26 % ab	27 % a
heading	35 % ab	23 % b	27 % ab	28 % ab	33 % ab	37 % ab	43 % a

Table 3: selected yield parameters

	C	S100	UU100	CU100	CU75	CU50	CU25
grain yield [dt ha^{-1}]	26.7 c	39.9 a	40.2 a	39.6 a	35.1 ab	33.5 abc	30.4 bc
protein content [%]	9.3 a	8.7 a	10.8 a	9.1 a	10.2 a	9.7 a	10.6 a
1000 kernel weight [g]	38.3 abc	40.4 a	39.7 ab	39.7 ab	38.1 bc	37.2 c	39.1 abc
ears per m²	356.4 a	393.3 a	398.2 a	406.2 a	361.3 a	378.2 a	357.3 a
grains per ear	19.9 c	25.2 a	25.3 a	24.6 a	25.4 a	23.7 ab	21.7 bc

Table 4: Nitrogen balance and Nitrogen use efficiency (NUE)

	protein yield [dt ha^{-1}]	N uptake [kg ha^{-1}]	fertilizer N [kg ha^{-1}]	soil N [kg ha^{-1}]	balance	NUE
C	2.5	39.9	0.0	32.9	-6.9	-
S100	3.5	55.7	70.0	35.2	49.5	0.8
UU100	4.3	69.2	70.0	33.5	34.3	1.0
CU100	3.6	57.5	70.0	32.1	44.5	0.8
CU75	3.6	56.9	52.5	33.3	28.9	1.1
CU50	3.1	49.9	35.0	32.3	17.4	1.4
CU25	3.2	51.4	17.5	33.5	-0.4	2.9

CONCLUSION

The expected possibility to harvest the same with reduced fertilization by an enhanced fertilizer type did not fulfil since the grain yield was not significantly higher than the unfertilized control for reduced variants. Therefore, we could not derive beneficial effects of the novel slow-release fertilizer from the results of this field trial. More field site years as well as further research on the laboratory scale to understand the short-term behaviour of the coated urea are needed.

ACKNOWLEDGEMENTS

This work was conducted as part of project SASCHA (Sustainable land management and adaption strategies under climate change for the Western Siberian grain belt). We are grateful for funding by the German ministry of education and research (BMBF) within their sustainable land management funding framework (funding reference 01LL0906D).

PICTURE CREDIT

Insa Kühling

Soybean flowers at Biostation Kuchak, 26 July 2013

2.5 Soybeans in high latitudes: Effects of *Bradyrhizobium* inoculation in northwest Germany and southern West Siberia [Org Agr (2017) 1-13]

AUTHOR CONTRIBUTIONS

Insa Kühling conducted the trial performed field measurements and post-harvest analyses in Russia, did all statistical analyses and wrote the manuscript
Bianka Hüsing conducted the trial in Germany
Nina Bome made the infrastructure available for the trial in Russia and organised harvest in Russia
Dieter Trautz contributed to the development of the experimental design in both trials and supervised Insa Kühling

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Organic Agriculture (2017) 1-13

SOYBEANS IN HIGH LATITUDES: EFFECTS OF *BRADYRHIZOBIUM* INOCULATION IN NORTHWEST GERMANY AND SOUTHERN WEST SIBERIA

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Submitted
12 January 2017
Accepted
18 April 2017

Keywords
Glycine max; nodulation; low root zone temperature; climate change; SPAD-502; organic agriculture

DOI: 10.1007/s13165-017-0181-y

ABSTRACT

In regions around the current high-latitude boundaries of agricultural production, the effects of climate change are likely to affect future growing conditions. Specifically for soybeans (*Glycine max* (L.) Merr.) this leads to a northwards shift of the northernmost limit for cultivation. In two high latitude regions with cold growing conditions (northwest Germany and southern West Siberia, Russia) similar field trials were conducted under different climate conditions (temperate oceanic, temperate continental). The effect of soybean seed inoculation with *Bradyrhizobium japonicum* was investigated in comparison to untreated control in five field site-years under organic farming conditions. SPAD-meter readings were used to indicate differences in leaf chlorophyll content between inoculation and control at three phenological development stages. To make SPAD-values from different varieties and development stages comparable, effect sizes ("Hedges' d" of inoculation against control) were calculated. Inoculation was always successful, significant numbers of active nodules developed only with inoculation. Effect sizes of SPAD-values were significantly positive in inoculated plots at beginning of seed filling but did not differ earlier. Except for the warmest site-year, inoculation did not affect seed yield. Protein content was significantly higher with inoculation at most varieties tested in Germany but only once in Russia. Protein yield was only in the warmest site-year significantly higher with inoculation. Under cold growing conditions of high latitude regions temperature sums seemed to limit soybean yield and the effectiveness of inoculation with *B. japonicum*. To implement soybeans as legumes in organic farming crop rotations, nevertheless, inoculation is mandatory, since soils at high latitudes lack soy-specific rhizobia bacteria.

INTRODUCTION

Soybean (*Glycine max* (L.) Merr.) is an important legume crop, contributing yearly 11 of 17 Tg biological nitrogen fixation (BNF) worldwide, equal to almost 20 % of the yearly total N demand for crop production (Herridge and Rose 2000). For successful BNF legume crops as well as their specific symbionts need optimal conditions. Soybeans as subtropical pulses with Asia as their centre of origin (Hymowitz 2004) are commonly cultivated in mid latitudes around the world. Breeding of soybean genotypes for a wide range of environmental conditions was quite successful during the last decades, particularly the adaptation to long day length. Nevertheless, soya cultivation is still in the beginning for high latitudes regions like Northern Germany (Zimmer et al. 2016) as well as Western Siberia (Gamzikov et al. 2008). So far, soybeans are commonly grown in the southern part of Germany and in the Far East in Russia due to more suitable climate conditions. Optimal temperatures for plant growth and nodulation are reported to be around 25 °C (Legros and Smith 1994). Therefore, selection for chilling tolerance was a key issue in soybean breeding (Gass et al. 1996) and strain development (Lynch and Smith 1994) for high latitude regions. Jia et al. (2014) tested genotypes from different geographical origin and found that these 'high latitude cold region' varieties were in general adapted up to 53° N. Furthermore, several *Bradyrhizobium* strains were identified to work under cold environments (Zhang et al. 2003). Stephens and Rask (2000), moreover, reported the advantage, that there is no competition with native rhizobia bacteria in high latitude soils, that usually lack these soy specific strains.

Climate change affects several strong interacting factors with different feedback for agricultural production. Agriculture in the northern hemisphere is likely to benefit from climate change and agriculture in global south will probably suffer the brunt of the impacts (Wheeler and Braun 2013; Zabel et al. 2014). Growing seasons lengthened by increasing temperatures may allow to grow crops with higher temperature requirements. Specifically soybeans are a promising new crop for this region experiencing shifting vegetation zones caused by climate change (Tchebakova et al. 2011). Besides temperature trends, also climate change induced elevation of CO_2 levels will affect agriculture. However, the expected CO_2 effects are likely to compensate heat stress in terms of crop production both, in northwest Germany (Kersebaum and Nendel 2014) and Western Siberia (Sirotenko et al. 1997). Among all C3 crops, legumes like soybeans can best utilise the elevated CO_2-concentrations resultant of global warming (Oikawa et al. 2010). In conjunction with breeding progress for daylength insensitive early maturity varieties climate change effects could allow for soybean cultivation in high latitudes regions with short seasons and low root zone temperatures (RZT) (Maracchi et al. 2005; Kiselev et al. 2013).

Against this background, soybeans could contribute to higher agro-biodiversity by a diversification of crop rotations in high latitudes (FAO 2004). Soybeans are known to have higher nitrogen (N) withdrawal by harvested grains than the amount of N they fixed from the atmosphere (Herridge and Rose 2000; Oberson et al. 2007). However, the contribution of 54 % by BNF is significantly higher under organic farming conditions compared to 24 % in conventional faming systems (Oberson et al. 2007). Therefore, especially organically grown soybeans are of interest for sustainable land management (SLM) strategies under climate change conditions (Scialabba and Müller-Lindenlauf 2010).

Whigham and Minor (1978, in Lynch and Smith, 1994) described the poor adaptability of soybeans and their *Bradyrhizobium japonicum* strains to low soil temperatures as the most limiting yield factor in short growing seasons of high latitudes. The aim of this study was to investigate the effect of soybean inoculation with *B. japonicum* on plant development and yield parameters at different early maturity varieties in two high latitude environments with cool growing conditions, i.e. northwest Germany and southwest Siberia within the framework of organic farming.

MATERIALS AND METHODS

Field trials and study sites

The fields of the German site were located at the organic experimental farm Waldhof (WH) of Osnabrück University of Applied Sciences in northwest Germany (52.32° N 8.04° E) and the Russian trials took place at Biostation Kuchak (BK) of Tyumen State University in the south of Western Siberia (57.35° N 66.06° E). The trials were conducted under organic farming conditions for three consecutive seasons at WH (GER) (2011-2013) and for two at BK (RUS) (2013-2014).

Soybean varieties from three early to very early maturity groups (MG) were grown at the two study sites: ES Mentor (MG 00), Gallec (MG 000/00) and Aveline (MG 000) at WH (GER) and Augusta, Aveline and Sibniik315 (all MG 000) at BK (RUS). Each year the soybeans were grown on different fields, always for the first time. The factorial experiment at both sites was designed as a split plot with inoculation as the main plot to avoid cross contamination among the treatments. The varieties were completely randomized arranged as subplots with four replications.

For inoculation treatment we used a peat based product (Force48, BASF) of *Bradyrhizobium* strain 532C (Hume and Shelp 1990). 4 g kg^{-1} seed ($2x10^9$ viable cells g^{-1}) according to the manufacturer recommendations were applied together with a liquid adhesive on the seeds directly before sowing. Cultivation at WH (GER) was rainfed and BK (RUS) was sprinkler irrigated as required (2 to 4 times a season). Detailed information about the soil conditions and timing of management operations in each year is summarised in **Table 1**.

Measurements

Nodulation

Number of nodules per plant were counted at 3 (BK) and 5 (WH) randomly selected and carefully uprooted plants per plot at full bloom stage (R2, Fehr and Caviness 1977).

Leaf chlorophyll

For estimation of leaf chlorophyll content we used a SPAD-502 chlorophyll-meter (Konica Minolta, Japan). The SPAD-meter computes a dimensionless value with larger numbers indicating higher chlorophyll content. The SPAD measurement is based on optical density differential calculated by the absorbance of a leaf at 650 nm wavelength (maximum absorbance of chlorophyll a and b) and the absorbance at 940 nm for adjustment of the leaf thickness. A detailed description of the SPAD measuring method can be found in Uddling et al. (2007). SPAD-meter readings were always taken from uppermost fully developed leaves, at WH (GER) from five and at BK (RUS) from 30 representative plants per plot. Sampling took place at three phenological development stages V3 (third node), R3 (beginning pod) and R5 (beginning seed) (Fehr and Caviness 1977).

Yield parameters

Harvest took place at physiological maturity, seed yield (g m^{-2}) and 1000-seed weight (TSW in g) was measured at 86 % dry matter. Seed crude protein content was calculated on the basis of the nitrogen content, determined according to the Kjeldahl method (European Union 2009).

Statistical analysis

SPAD-meter readings are known to be significantly influenced by leaf developmental stage and genotype (Ma et al. 1995; Fritschi and Ray 2007; Teklić et al. 2009). Thus, effect sizes were used to make the SPAD values of different varieties and different development stages comparable. ‘Hedges’ d’ was calculated according to Nakagawa and Cuthill (2007) as follows:

$$d = \frac{\bar{x}_{treat} - \bar{x}_{control}}{s_{pooled}} \left[1 - \frac{3}{4(n_{treat} + n_{control} - 2) - 1}\right] \qquad (1)$$

$$s_{pooled} = \sqrt{\frac{(n_{treat} - 1)s_{treat}^2 + (n_{control} - 1)s_{control}^2}{n_{treat} + n_{control} - 2}} \qquad (2)$$

The effect size (d), was computed as difference of the means ($\bar{x}$) between inoculated with *Bradyrhizobium japonicum* ($treat$) and untreated $control$ without inoculation divided by the pooled standard deviation (s). The second term corrects for bias of small sampling sizes (n).

For check of significance and visualisation in forest plots the standard errors (SE) of Hedges’ d were calculated after equation (3).

$$SE_d = \sqrt{\frac{n_{treat} + n_{control}}{n_{treat}\, n_{control}} + \frac{d^2}{2(n_{treat} + n_{control} - 2)}} \qquad (3)$$

Average effect sized ($\bar{d}$) over time and varieties were computed after equation (4) with weighting factor (w) and the related standard deviation.

$$\bar{d} = \frac{\sum_{i=1}^{n} w_i d_i}{\sum_{i=1}^{n} w_i}$$

$$\text{with} \quad w = \frac{1}{SE_d^2} \quad \text{and} \quad SE_{\bar{d}} = \sqrt{\frac{1}{\sum_{i=1}^{n} w_i}} \qquad (4)$$

For yield results, we conducted an analysis of variance (ANOVA) followed by a Tukey HSD post-hoc test if significant differences were observed. Probabilities <0.05 were considered to indicate statistical significance. All statistical analyses were done with R (R Core Team 2013), using the additional packages agricolae (de Mendiburu 2014) and metafor (Viechtbauer 2010).

Table 1: Details of the field trials at the two study sites Waldhof in Germany (WH GER) and Biostation Kuchak (BK RUS) in Russia for the five field-site-years with management operations and soil and climate conditions.

	WH (GER)			**BK (RUS)**	
	2011	**2012**	**2013**	**2013**	**2014**
Experimental set up					
Previous crop	potatoes	potatoes	potatoes	spring barley	peas
Row spacing	37.5			15	
Plants m^{-2}	65			65	
Plot size [m^2]	15 (1.5 harvest)			0.6	
Sowing date [dd.mm]	27.04	30.04	05.05	15.05	19.05
Harvest date [dd.mm]	09.10	20.10	02.10	24.09	09.10
Soil conditions					
Soil pH	5.5	5.5	6.0	5.2	5.2
N_{min} 0-30cm [(NO_3-N+NO_4-N) kg ha^{-1}]	52.6	67.3	51.4	<30	<30
Soil type[a]	Planosol	Planosol	Planosol	Podzol	Podzol
Soil texture	loamy sand	sandy loam	sandy loam	loamy sand	loamy sand
Climate conditions					
Climate zone[b]	temperate oceanic (Cfb)			temperate continental (Dfb)	
Mean annual precipitation [mm][c]	861			483	
Mean annual air temperature[c] (min – max) [°C]	10.1 (+6.0 – +14.2)			2.3 (-2.5 – +7.1)	
Mean growing degree days (GDD)[cd] [°C]	976			724	
Mean growing season length (GSL)[ce] [days]	179			132	

[a] according to the WRB system (FAO 2014)

[b] classification after Köppen/Geiger (Peel et al. 2007)

[c] long term average 1981-2010 (DWD 2015; TUTIEMPO 2016b)

[d] calculated as sum of $T_{mean} - T_{base}$ with $T_{mean} = \frac{T_{min}+T_{max}}{2}$ and $T_{base} = 10\,°C$ where T_{mean} was set to T_{base} in case of $T_{mean} < T_{base}$ (McMaster and Wilhem 1997)

[e] based on 10 °C

RESULTS

Weather conditions and phenological plant development

WH (GER) showed very similar temperature development from 933 to 1041 growing degree days (GDD), during the three trial years with the long-term average (**Figure 1**A, **Table 2**). Hence, variation in plant development was little with differences between 1 and 6 days for reaching the same stages. At BK (RUS) GDD in both years differed clearly from the long-term average, beginning with cooler conditions during juvenile development and ending with an overall cooler growing season in 2014 (631 GDD) and a higher temperature sum in 2013 (820 GDD) (**Figure 1**B). Consequently, development time from one growth stage to the next differed at BK (RUS) considerably between 8 and 15 days.

Relative differences of the yearly GDD compared to the long-term average were less pronounced at WH

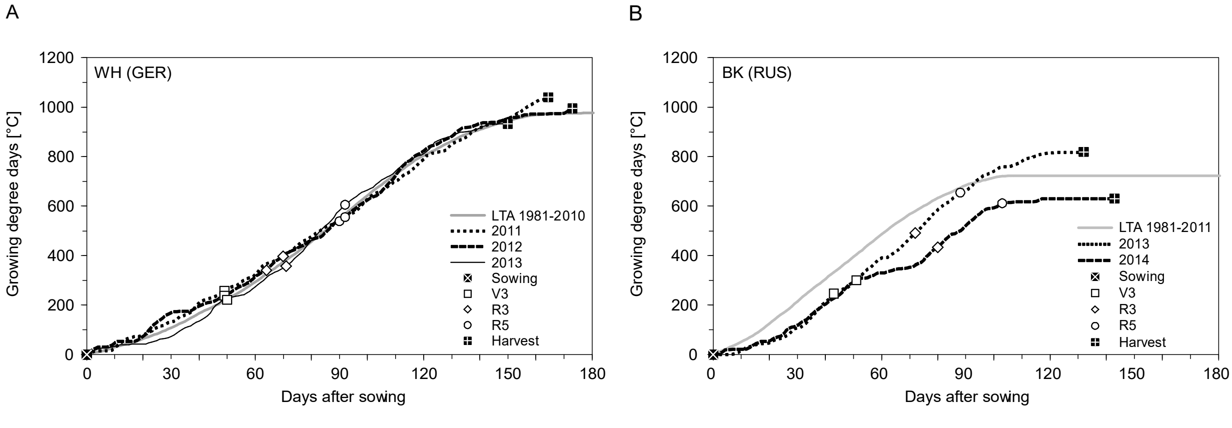

Figure 1: Summed temperatures above 10 °C (growing degree days, GDD) after sowing dates for the corresponding site-years at Waldhof (WH GER) and Biostation Kuchak (BK RUS) in comparison with the long-term average (LTA) from 1981 to 2010. Marked development stages V3: third node, R3: beginning pod, R5: beginning seed. Data source: DWD (2015), TUTIEMPO (2016b).

(GER) than at BK (RUS) (**Table 2**). Whilst the early development at the German site was in 2011 and 2012 warmer (+20 and +48 %, respectively), 2013 was slightly cooler (-3 %). Differences diminished during continuing development phases, over the entire growing season the temperature sums differed between +6 % in 2011 and -1 % in 2013. At the Russian site, in particular the beginning of the growing season (vegetative development until flowering) was markedly cooler by up to -61 % of the average GDD. During the later stage, the year 2013 turned into an above average season whereas 2014 stood cooler. In total, the two seasons at BK (RUS) varied 13 % around the long-term mean.

Soil temperatures were continuously recorded at 10 cm depth in 2014 at BK (RUS) and showed average values (± standard deviation) by 14.6 ±1.0 °C in May, 21.3 ±2.5 °C in June, 15.3 ±2.8 °C in July and 17.0 ±2.3 °C in August.

Nodulation

Inoculation with *Bradyrhizobium japonicum* was successful at both sites in all investigated years (for the German site investigated only in one year) (**Table 3**). All plots with inoculated seeds showed significant more nodules, at BK (RUS) no single nodule developed without inoculation, at WH (GER) only very few nodules appeared (**Figure 2**). Nodules of all plants were predominantly located at the crown roots. At WH (GER) we also observed a significant variety effect as well as a significant inoculation × variety interaction.

Overall, the number of nodules was larger at WH (GER) compared to BK (RUS). The regional Siberian variety Sibniik315 nodulated as an outlier and showed especially in 2013 much larger variation than all other site-years (**Table S1**).

Leaf chlorophyll

The measured SPAD values as estimation for leaf chlorophyll content showed different responses on inoculation over time and between the two study sites. The calculated effect sizes for SPAD-meter readings of inoculated plots compared to control were mainly not significantly different at the first measuring during the vegetative growth (V3) (**Figure 3**). At the second measuring during beginning of pod development (R3) we observed predominantly non-significant responses at WH (GER) with two significantly negative effects in 2013 (varieties Aveline and Gallec). In Russia, the SPAD-meter readings from R3 stage resulted in significant positive effect sizes except for Aveline in 2013. At the latest sampling date during the beginning of seed filling, the measured SPAD data resulted predominantly in positive and significant effect sizes. For both investigated sites, the impact of seed inoculation on leaf chlorophyll content was slightly different between the varieties, altogether, Aveline showed the best performance. Compared to the German SPAD measurements, variation was higher at the Russian site.

Yield parameters

For the seed yield at WH (GER) we observed a significant inoculation (I) effect, but also a significant inoculation × year interaction (**Table 3**). Due to large differences between the weather conditions of the studied years at BK (RUS) (**Figure 1, Table 2**) post-hoc tests were only conducted for inoculation × variety, but separately for each year for both locations. Thus, the seed yields in Germany showed that only one variety (ES Mentor) in one year (2011) yielded significantly higher seed yield by inoculation (**Figure 4**A). At BK (RUS) the seed yield was never significantly affected by inoculation, but by variety and year (**Table 3, Figure 4**B). The inoculation of the seeds led to a highly significant effect on seed protein content at both sites (Table 3). Furthermore, protein content was significantly affected by year and at BK (RUS) additionally by variety. Therefore, the separate by year post-hoc tests predominantly revealed significantly higher protein contents for the German site whereas only two varieties in 2014 got significantly more protein after inoculation at the Russian site (**Figure 4**). Significant interactions between all factors affected the TSW at both locations. Only in 2011 at WH (GER) inoculation led to significantly higher TSW for two of three varieties (**Table S1**).

Table 2: Weather characteristics of the growing seasons at Waldhof (WH GER) and Biostation Kuchak (BK RUS) with number of days, mean daily air temperatures (T_{mean}), growing degree days (GDD, 10°C base) and relative differences of GDD to the long-term average for the corresponding site for the phases between selected development stages. V3: three nodes with fully developed leaves, R3: beginning of pod development, R5: beginning of seed filling. Data source: DWD (2015), TUTIEMPO (2016b).

	WH (GER)											
	2011				**2012**				**2013**			
	Days	T_{mean}	GDD		Days	T_{mean}	GDD		Days	T_{mean}	GDD	
Vegetative growth (sowing – V3)	49	15.0	258	+20 %	49	14.4	238	+48%	50	14.2	222	-3 %
Flowering (V3 – R3)	21	16.7	141	+14 %	15	17.5	103	+7%	21	16.2	135	-5 %
Pod development (R3 – R5)	20	17.1	141	+5 %	28	17.5	215	+1%	21	21.8	249	+1 %
Seed filling (R5 – harvest)	74	16.5	501	-1 %	81	15.1	440	+1%	58	15.6	327	+2 %
Total (sowing – harvest)	164	16.3	1041	+6 %	173	16.1	996	+2 %	150	17.0	933	-1 %

	BK (RUS)							
	2013				**2014**			
	Days	T_{mean}	GDD		Days	T_{mean}	GDD	
Vegetative growth (sowing – V3)	43	15.2	247	-61 %	51	15.5	301	-44 %
Flowering (V3 – R3)	29	18.5	245	-22 %	29	14.5	133	-33 %
Pod development (R3 – R5)	16	20.2	163	-9 %	23	17.7	178	-23 %
Seed filling (R5 – harvest)	44	13.1	164	+7 %	40	7.4	18	-14 %
Total (sowing – harvest)	132	16.8	820	+13 %	143	13.8	631	-13 %

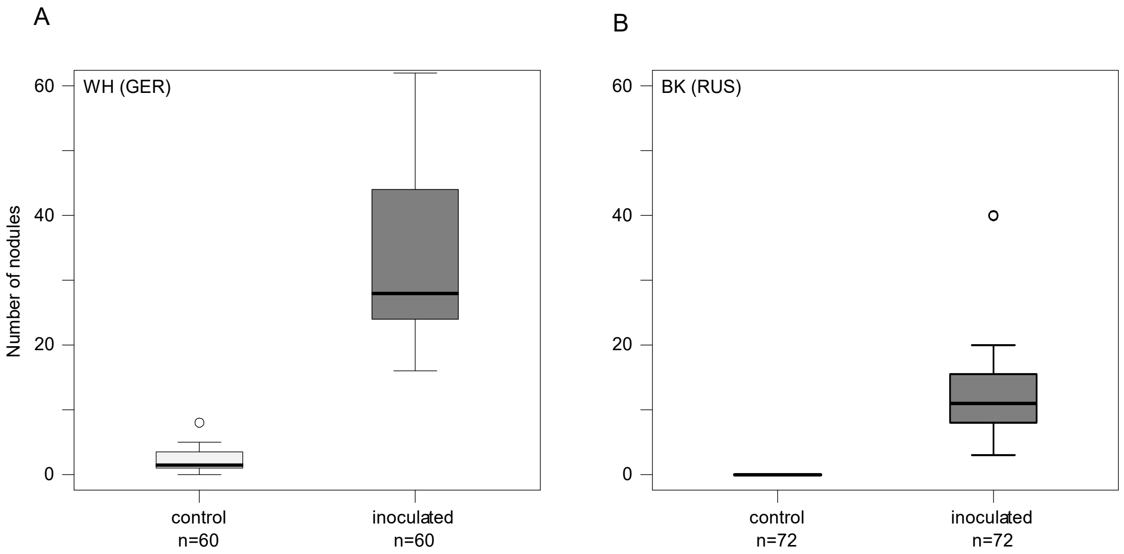

Figure 2: Average number of nodules for inoculated seeds and control plots (without inoculation) at Waldhof in Germany (A) and Biostation Kuchak in Russia (B). Nodules were counted at three (BK RUS) and five (WH GER) uprooted plants from each plot during full bloom (R2 stage) in 2011 at the German site and in 2013 and 2014 at the Russian site.

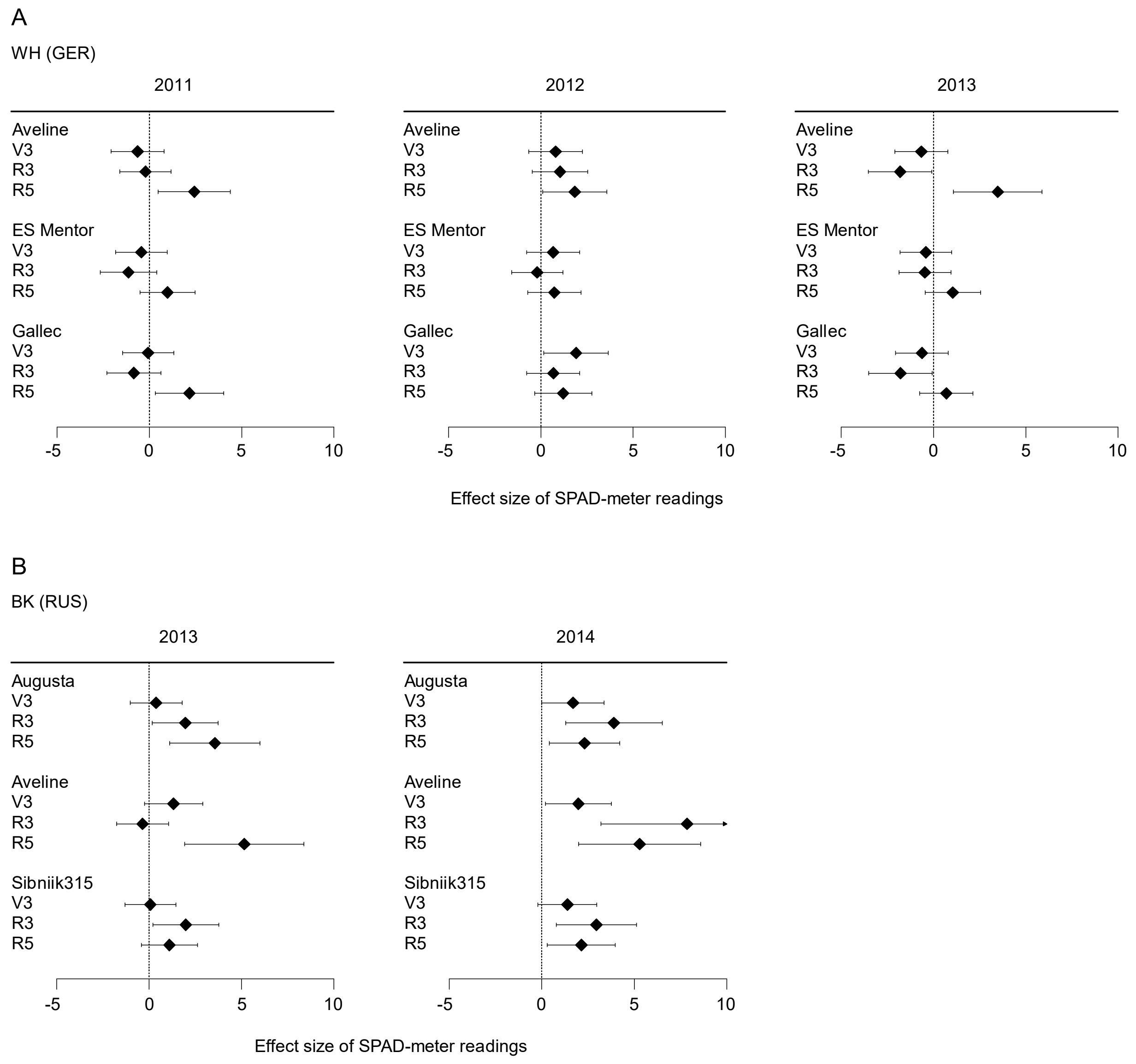

Figure 3: Calculated effect sizes of SPAD-meter readings from inoculated plants compared to control (without inoculation) at three development stages for the two study sites Waldhof (WH GER) and Biostation Kuchak (BK RUS) for different varieties. V3: three nodes with fully developed leaves; R3: beginning of pod development; R5: beginning of seed filling.

DISCUSSION

We observed significantly better development of active nodules and for several varieties and years significantly higher SPAD values after seed preparation with *B. japonicum* inoculum. SPAD-meter readings provide reasonable estimates of leaf chlorophyll content (Markwell et al. 1995; Thompson et al. 1996) and are further known to be a valuable indicator for leaf nitrogen supply (Fritschi and Ray 2007). Consequently, we assumed to find a functioning symbiosis for biological nitrogen fixation (BNF) by the used *B. japonicum* strain 532C under the given root zone temperatures (RZT) at our two studied sites in Northern Germany (WH GER) and Western Siberia (BK RUS).

Nodulation and BNF

In our trials we found considerably fewer numbers of nodules per plant (33 and 12 on average for WH (GER) and BK (RUS), respectively) than reported by other studies (e.g. Danso and Bowen 1989; Lynch and Smith 1994). The poor nodule development could be influenced by low RZT (Matthews and Hayes 1982; Legros and Smith 1994; Zhang et al. 1995) since our soil

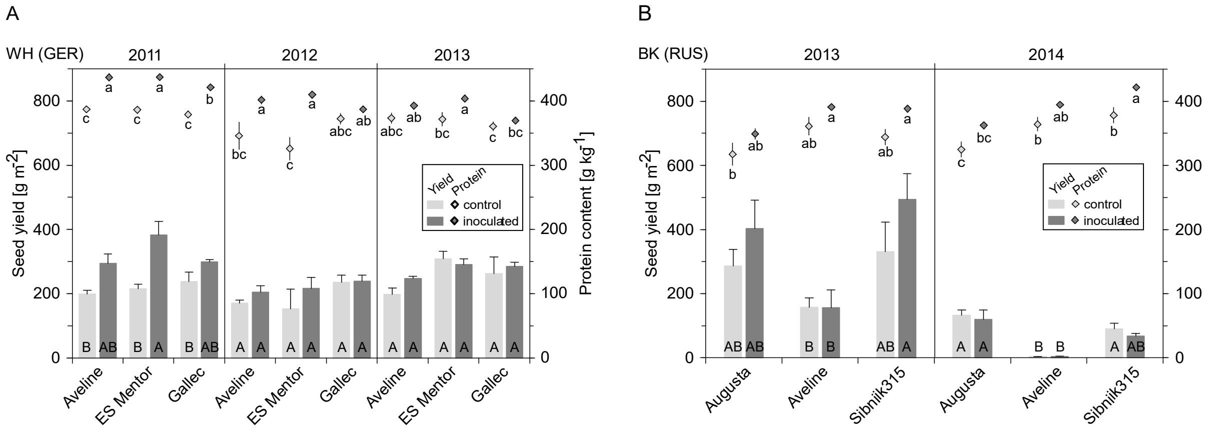

Figure 4: Harvest parameters seed yield (bars) and protein content (rhombs) with significance levels (p=0.05) for all varieties within each year at Waldhof (WH GER) (A) and Biostation Kuchak (BK RUS) (B). Mean values of four replicates with 1SE as error bars.

Table 3: p-Values from ANOVA for the two study sites Waldhof in Germany (WH GER) and Biostation Kuchak in Russia (BK RUS) for nodulation counted at R2 stage (full bloom) and yield parameters seed yield, thousand seed weight (TSW), protein content and protein yield recorded after harvest.

Site		Nodulation [nodules plant^{-1}]*	Seed yield [g m^{-2}]	TSW [g]	Protein content [g kg^{-1}]	Protein yield [g m^{-2}]
WH (GER)	Variety (V)	**0.006**	**0.049**	**<0.001**	0.239	0.131
	Inoculation (I)	**<0.001**	**0.001**	**<0.001**	**<0.001**	**<0.001**
	Year (Y)	-	0.731	**<0.001**	**<0.001**	0.170
	V × I	**0.003**	0.518	**0.024**	**0.043**	0.524
	V × Y	-	0.793	0.769	0.736	0.889
	I × Y	-	**0.020**	0.766	**0.023**	**0.009**
	V × I × Y	-	0.220	0.158	0.862	0.329
BK (RUS)	Variety (V)	0.471	**<0.001**	**<0.001**	**<0.001**	**<0.001**
	Inoculation (I)	**<0.001**	0.179	**0.012**	**<0.001**	0.056
	Year (Y)	0.341	**<0.001**	**<0.001**	**0.009**	**<0.001**
	V × I	0.471	0.602	0.496	0.599	0.413
	V × Y	0.240	0.052	**<0.001**	0.088	0.060
	I × Y	0.341	0.085	**0.019**	0.861	**0.040**
	V × I × Y	0.240	0.424	0.391	0.964	0.320

* for WH (GER) only 2011 was taken into account due to lack of data.

temperature recordings from 2014 showed sub-optimal RZT for nodulation and BNF (mostly described below 25 °C) over the entire growing season at the Russian site. In detail, Zhang et al. (1995) reported a linear delay of 2.5 days per °C between inoculation and the onset of BNF for temperatures below 25 °C, 7.5 days below 17 °C, and a steep decrease below 17 °C. Nevertheless, sub-optimal RZT were described to affect nodulation more adversely than the activity of existing nodules (Matthews and Hayes 1982; Lynch and Smith 1993). The used *B. japonicum* strain 532C was described as well adapted to low RZT (Lynch and Smith 1994). Although Zhang et al. (2003) identified better strains under cold conditions, they showed still significant better performance of strain 532C inoculum compared to not inoculated control.

The nodules on the observed plants developed primarily around the crown roots, similar as summarized by Salvagiotti et al. (2008) for inoculation procedures, where the inoculum was applied on the seeds. The low migration of *B. japonicum* in the soil was also described by Danso and Bowen (1989). Hardarson et al. (1989) further reported that nodule position significantly influenced the N-fixation with the better performance by lower located and later developed nodules, such as after inoculum application to the soil below the seeds.

In contrast to subtropical soils where soybeans have their center of origin, there is no competition with indigenous rhizobia bacteria when soybeans are grown on soils at high latitudes like in Germany (Zimmer et al. 2016) or Russian Siberia (Gamzikov et al. 2008). Hence, neither nodulation nor the amount of BNF was dependent on the competitive ability of the strain we used (Montañez et al. 1995). Earliness of nodulation is furthermore described as a critical trait for successful symbiosis (Weaver and Frederick 1972), but seems to be less important in soils of high latitudes that lack indigenous strains.

Although SPAD-metering estimates the chlorophyll content, it is commonly used as a proxy of N-supply of the plant, for example to calculate fertilizer amounts or for breeding purposes. In particular, within a narrow genotype variation (like in one variety) it is possible to assess reliable leaf N-contents by SPAD-metering (Fritschi and Ray 2007). Sinclair et al. (2004) described a strong relationship between leaf N and photosynthesis. Gwata et al. (2004) found a direct positive correlation between leaf colour score and BNF. Additionally, a consistent correlation between SPAD-meter readings and photosynthetic rate during R4 to R5 growth stages was reported by Ma et al. (1995).

To make our SPAD-meter readings comparable between different development stages and genotypes, we calculated effect sizes. The results from our high latitude sites showed a later onset of BNF compared to other studies located less north. In our trials, differences between inoculated seeds and control were only in selected site-years significant at V3 and R3 stage (2 out of 5), but in all site-years at R5 stage. Vollmann et al. (2011) observed already from V5 stage onwards significant differences from trials in Vienna, Austria (latitude ≈48° N). Furthermore, Zapata et al. (1987) found the maximal BNF from R3 to R5 stages, whereas our investigations showed a later average peak.

The cooler growing season at WH (GER) in 2013 led to a significant negative effect size of inoculation on BNF. The above average season 2012 with high temperatures especially in the beginning led to earlier significant effects (V3). The same pattern was found at BK (RUS), where in the above average season 2014 significant differences were already observed during V3 whilst in the cooler season 2013 the positive effect occurred only in R5.

Summarised, our data confirmed the temperature sensitivity of nodulation as well as the possibility of successful inoculation with active nodules and advantages in leaf nitrogen supply as described by Lynch and Smith (1993). Even though a delay of nodulation under low soil temperatures was observed, we could assume a significant N-supply by BNF after inoculation in our high latitude experiments.

Climate impact and phenological development

We found a total duration of 150-173 days from sowing to maturity for WH (GER) and 132-143 days for BK (RUS), respectively. Possible shorter development by 82-125 days to maturity were observed for Soybeans in China (N 50°15'), but they were grown under much higher mean temperatures (Jia et al. 2014; Wu et al. 2015). Nevertheless, Egli (2011) stated, that the length of the reproductive phase is more important for yield than total growth duration. He summarised from 20 studies a mean of 111 days (range 86-141) for the total duration from sowing to maturity and found an average proportion of 34 % (range 25-52) for reproductive phase. From our trials, we also found a positive correlation of seed yield and proportion of the generative growth, more pronounced with inoculation than in control (R^2 0.62 and 0.45, respectively). Besides this, however, we got a reciprocal ratio of 39 % (49-64 days) for the vegetative development and 61 % (83-109 days) for the reproductive phase. Another trial, conducted over three years in a cool organically managed environment in Germany at 51.4° N 9.4° E by Zimmer et al. (2016) showed a mean proportion of 52 % (84 days) for the reproductive phase but neither with a clear response on yield nor inoculation. Furthermore, the reduced growing season length (12 compared to 6 months) was mentioned as the main reason for a reduced total yearly productivity, estimated from solar radiation during temperatures above 10 °C by -50 % in high latitudes (>50° N) compared to the tropics (Egli 2011). Interestingly, the proportions of the GDD for vegetative and generative phase from the trials at our study sites showed very similar ratios to the duration in days. Within the five site-years, the highest and poorest yield results (WH GER 2011 and BK RUS 2014) were derived from the warmest and coolest season (+3 % and -13 % GDD), respectively. Moreover, the only season with significant yield effects from inoculation was the warmest one (1041 GDD). Hence, soybean performance under cool conditions in high latitudes seems to be primarily temperature limited.

Yield effects

Egli (1993) identified the number of seeds per m^2 and the duration of seed filling phase as the two main yield-determining factors. The positive correlation between seeds per m^2 and seed yield was only present at the German site (R^2 0.68) but not at the Russian (R^2 0.14), without any respond on inoculation. The duration of seed filling phase helped very little to explain yield differences, but again the GDD during seed filling were especially for the Russian site correlated with the seed yields.

Negative effects of stress by low temperature during the reproductive development were described as a yield reducing effect (Kurosaki and Yumoto 2003). In our trials, there were no differences in response to temperatures or distribution into vegetative and generative growth between inoculation and control treatments. Since we could not observe signs for stress phase of cool temperature during flowering, we concluded, that in our high latitude environments the total sum of temperature (GDD) was the more limiting factor.

Inoculation with *B. japonicum* not necessarily results in better soybean yield. Studies from India (Appunu et al. 2008) or Eastern Germany (Zimmer et al. 2016) showed the same findings as our trials. No effect of inoculation on seed yields is well known for soils high soil N availability or mineral N fertilization (Albareda et al. 2009), but cannot explain our results under organic farming conditions with low plant available N-content and relatively poor soil fertility. In particular, in years with below average temperature sums, the delay of maturity due to better N-supply by BNF seemed to dominate over positive yield effects. We observed only in the warmest site-year (GER 2011 with 1041 GDD) significant higher seed yields with inoculation, but always a clear effect on yield quality in terms of protein content. Moreover, Silva et al. (2013) identified further health-promoting effects by enhanced metabolic compounds in soybeans after inoculation with *B. japonicum*. Due to the preceding crop effect of soybeans, also the yield effect of the following crop has to be taken into account for a final evaluation. Gamzikov et al. (2008) estimated highest benefits of soybeans with inoculation for the following spring wheat from a comparison of several pulses.

Climate change perspectives

Under the perspectives of climate change, special focus on drought tolerant varieties is necessary to maintain good BNF in our high latitude study regions (King and Purcell 2001). Regardless of the temperature stress, for both, Northwestern Germany and the south of Western Siberia, beneficial effects for crop production by elevated CO_2 concentrations are predicted by modelling (Sirotenko et al. 1997; Kersebaum and Nendel 2014). Legume species, in particular those with high seed N-content like soybeans, could specifically benefit from elevated CO_2 levels (Oikawa et al. 2010). Furthermore, promising results from co-inoculation with other plant growth promoting rhizobacteria (PGPR) and arbuscular mycorrhizal fungi revealed high potential for improvements of future soybean cultivation in high latitudes (Zhang et al. 1997; Dashti et al. 1998; Groppa et al. 1998; Meghvansi et al. 2008; Masciarelli et al. 2014).

CONCLUSION

We observed successful nodulation and active nodules, SPAD-meter readings indicated functioning BNF but in the studied environments, the soybean plants did not transfer advantages of the symbiosis into higher seed yields. Delay of maturity due to better N-supply by BNF seemed to dominate over positive yield effects, since only in the warmest site-year (GER 2011 with 1041 GDD) seed yields were significantly higher with inoculation. Since the protein content was always positively affected by inoculation, it makes sense to focus on the protein yield for final evaluation. Nevertheless, protein yield was only positively affected by inoculation in one site-year (GER 2011) as well.

In the framework of organic farming, soybeans could only contribute in a sustainable way to more agro-biodiversity, if they supplement the legume position in the crop rotation. For substituting other well-adapted pulses in the cropping sequence, inoculation with *Bradyrhizobium* is mandatory, even if it will not result in higher yield.

ACKNOWLEDGEMENTS

The trials at BK (RUS) were conducted as part of project SASCHA (‘Sustainable land management and adaptation strategies to climate change for the Western Siberian grain belt’). We are grateful for funding by the German Government, Federal Ministry of Education and Research within their Sustainable Land Management funding framework (funding reference 01LL0906D). The trials at WH (GER) took place within the project ‘Expansion of soybean cultivation in Germany through adaptation by breeding as well as optimization of crop production and processing technology’ funded by the German Government, Federal Ministry of Food and Agriculture within their BÖLN framework (funding reference 11NA002). We thank M. Kohlbrecher, M. Vergara and T. Zurheide for data collection at WH (GER) and A. Simerly for English language improvement. Finally, we acknowledge the valuable anonymous reviewer comments that helped to improve the manuscript.

Table S1::Mean values (± standard error) for nodulation (number of nodules during full bloom (R2)), seed yield, thousand seed weight (TSW), protein content and protein yield for the tested varieties at Waldhof (WH GER) and Biostation Kuchak (BK RUS). Multiple comparisons with Tukey HSD-test (p=0.05), no difference between same letters within each year.

Site	Year	Variety	Treatment	Nodulation*			Seed yield [g m^{-2}]			TSW [g]			Protein content [g kg^{-1}]			Protein yield [g m^{-2}]		
WH (GER)	2011	Aveline	control	2.5	(± 1.9)	c	198.8	(± 12.1)	b	198.9	(± 6.2)	c	386.7	(± 4.7)	c	76.8	(± 3.9)	c
			inoculation	21.4	(± 1.8)	b	294.8	(± 29.1)	ab	235.6	(± 9.8)	ab	436.2	(± 2.0)	a	128.6	(± 12.7)	ab
		ES Mentor	control	2.0	(± 0.5)	c	215.1	(± 13.9)	b	209.7	(± 3.5)	c	386.1	(± 1.4)	c	83.0	(± 5.4)	bc
			inoculation	47.6	(± 6.7)	a	383.0	(± 42.7)	a	258.7	(± 2.0)	a	436.7	(± 3.0)	a	167.0	(± 17.8)	a
		Gallec	control	3.4	(± 0.7)	c	237.7	(± 29.0)	b	223.8	(± 4.5)	bc	378.8	(± 4.0)	c	89.8	(± 10.3)	bc
			inoculation	31.3	(± 4.5)	b	299.5	(± 6.5)	ab	236.3	(± 3.8)	ab	421.1	(± 2.6)	b	126.1	(± 2.6)	ab
		CV [%]		104%			29%			10%			6%			33%		
	2012	Aveline	control	n.a.			171.2	(± 8.6)	a	190.4	(± 8.0)	b	345.6	(± 21.2)	bc	59.7	(± 6.9)	a
			inoculation	n.a.			205.2	(± 18.8)	a	198.2	(± 8.4)	ab	401.6	(± 6.3)	a	82.5	(± 7.9)	a
		ES Mentor	control	n.a.			153.0	(± 60.9)	a	198.2	(± 11.2)	ab	244.2	(± 82.7)	c	50.9	(± 21.6)	a
			inoculation	n.a.			217.3	(± 33.0)	a	230.2	(± 5.0)	a	409.8	(± 4.3)	a	88.7	(± 12.8)	a
		Gallec	control	n.a.			235.6	(± 21.7)	a	210.7	(± 5.3)	ab	279.2	(± 93.3)	abc	71.7	(± 24.1)	a
			inoculation	n.a.			238.5	(± 18.9)	a	197.8	(± 4.1)	ab	386.7	(± 3.5)	ab	92.4	(± 8.1)	a
		CV [%]					23%			9%			10%			27%		
	2013	Aveline	control	n.a.			197.8	(± 19.9)	a	170.6	(± 5.1)	b	373.1	(± 8.2)	abc	74.0	(± 8.4)	a
			inoculation	n.a.			246.4	(± 7.5)	a	189.8	(± 3.9)	ab	392.4	(± 5.3)	ab	96.7	(± 3.6)	a
		ES Mentor	control	n.a.			307.8	(± 24.5)	a	183.1	(± 7.7)	ab	371.4	(± 10.7)	bc	113.9	(± 7.6)	a
			inoculation	n.a.			290.4	(± 17.4)	a	229.0	(± 3.8)	a	403.4	(± 4.8)	a	117.1	(± 6.8)	a
		Gallec	control	n.a.			262.3	(± 51.2)	a	175.0	(± 4.1)	b	360.3	(± 7.1)	c	94.6	(± 18.8)	a
			inoculation	n.a.			284.7	(± 13.1)	a	217.2	(± 24.1)	ab	369.2	(± 3.9)	bc	105.2	(± 5.6)	a
		CV [%]					22%			15%			5%			23%		
BK (RUS)	2013	Augusta	control	0	-		286.2	(± 52.3)	ab	319.2	(± 40.5)	b	317.8	(± 17.2)	b	93.3	(± 20.7)	ab
			inoculation	9.8	(± 3.0)		402.9	(± 88.9)	ab	531.0	(± 128.7)	ab	349.3	(± 8.2)	ab	142.5	(± 33.8)	ab
		Aveline	control	0	-		157.9	(± 29.2)	b	246.6	(± 12.4)	b	361.3	(± 13.9)	ab	57.4	(± 11.9)	b
			inoculation	12.0	(± 1.1)		156.5	(± 55.9)	b	302.4	(± 49.7)	b	391.0	(± 4.0)	a	61.6	(± 22.5)	b
		Sibniik315	control	0	-		331.5	(± 92.4)	ab	570.2	(± 143.3)	ab	344.3	(± 12.1)	ab	111.9	(± 27.7)	ab
			inoculation	19.5	(± 7.3)		493.6	(± 80.5)	a	839.8	(± 50.4)	a	388.8	(± 1.2)	a	192.1	(± 32.0)	a
		CV [%]		139%			58%			55%			9%			60%		
	2014	Augusta	control	0	-		132.4	(± 16.5)	a	97.1	(± 3.7)	b	324.8	(± 11.9)	c	43.6	(± 7.1)	a
			inoculation	13.3	(± 1.5)		119.5	(± 29.7)	a	91.7	(± 7.3)	bc	362.5	(± 4.0)	bc	43.6	(± 11.3)	a
		Aveline	control	0	-		3.8	(± 0.7)	b	65.6	(± 4.3)	c	364.3	(± 10.5)	b	1.4	(± 0.2)	b
			inoculation	9.2	(± 3.1)		4.1	(± 1.1)	b	84.1	(± 12.4)	bc	394.8	(± 3.8)	ab	1.6	(± 0.4)	b
		Sibniik315	control	0	-		89.8	(± 18.7)	a	148.8	(± 5.8)	a	378.3	(± 12.0)	b	33.5	(± 6.3)	a
			inoculation	10.1	(± 2.5)		67.3	(± 8.5)	ab	155.5	(± 2.3)	a	421.8	(± 2.5)	a	28.4	(± 3.5)	ab
		CV [%]		120%			85%			34%			9%			83%		

*n.a.: not available; no ANOVA for nodulation at BK (RUS) due to lack of variance in the control datase

Table S2: Mean effect sizes of all varieties at the three development stages (V3: third-node, R3: beginning pod, R5: beginning seed) and mean effect sizes of all stages for each variety at the two study sites Waldhof (WH GER) and Biostation Kuchak (BK RUS). n.s.: not significant, *: p<0.05, **: p<0.01, ***:p<0.001.

Site	Year	Variety	Stage	Effect size	Standard error	
WH (GER)	2011	all	V3	-0.38	0.41	n.s.
		all	R3	-0.70	0.43	n.s.
		all	R5	1.70	0.51	***
		Aveline	all	0.17	0.45	n.s.
		ES Mentor	all	-0.20	0.43	n.s.
		Gallec	all	0.16	0.45	n.s.
	2012	all	V3	1.03	0.45	*
		all	R3	0.47	0.42	n.s.
		all	R5	1.19	0.46	**
		Aveline	all	1.16	0.46	*
		ES Mentor	all	0.39	0.42	n.s.
		Gallec	all	1.18	0.46	*
	2013	all	V3	-0.57	0.42	n.s.
		all	R3	-1.23	0.47	*
		all	R5	1.27	0.49	**
		Aveline	all	-0.33	0.51	n.s.
		ES Mentor	all	0.01	0.42	n.s.
		Gallec	all	-0.45	0.45	n.s.
BK (RUS)	2013	all	V3	0.53	0.43	n.s.
		all	R3	0.93	0.48	n.s.
		all	R5	2.25	0.61	***
		Augusta	all	1.42	0.51	**
		Aveline	all	0.84	0.51	n.s.
		Sibniik315	all	0.90	0.45	*
	2014	all	V3	1.66	0.49	***
		all	R3	3.85	0.80	***
		all	R5	2.65	0.63	***
		Augusta	all	2.33	0.58	***
		Aveline	all	3.25	0.76	***
		Sibniik315	all	2.00	0.54	***

Chapter 3

General Discussion

3.1 The need for sustainable land management in Western Siberia

Global significance of Western Siberian agriculture

The future of agriculture is challenged worldwide by the growing demand for food, fodder and fibre as well as increasing pressure on fertile soils. By a narrow definition of calories per capita, global agriculture currently produces enough for feeding the world population (FAO, WFP and IFAD, 2012). Some prognoses predict the same for the future population of 9 to 10 billion people, with a growing problem of allocation. Even though Western Siberia has a relatively short history of agricultural land use (Durgin 1962; Selezneva 1973), it plays a key role in grain production today (Liefert et al. 2010). Beyond agricultural production, global ecosystem services such as carbon sequestration, water cycling, biodiversity or global climate regulation are strongly influenced by the ecosystems of Western Siberia (Bukvareva et al. 2015). Therefore, the need for SLM strategies is not only of regional or national interest, but reflects global goals. Moreover, the strict rejection of GMO in Russian agriculture by the federal government is a great opportunity to maintain a large, pristine area of over 17 million km^2. As the FAO stated in 2008, no technology should be excluded to feed the growing word population (Tittonell 2014), Russia's role as a GMO opponent has become important.

Consequences of land-use change

The massive, politically induced land-use changes in Western Siberia caused manifold ecological and socio-economic consequences. Going back to the virgin lands campaign, soil degradation is a major issue across the grain belt. Currently already 20.3 % of the agricultural soils suffer from wetness, 19.5 % from erosion (wind and water) and 35.1 % from salinization (Mueller et al. 2015). The second wave of enormous land-use change took place after the collapse of the state farm system, when up to 30 % of the cropland was abandoned (ROSSTAT 2016). Large-scale estimations, mainly based on modeling, report a huge potential for carbon sequestration in the abandoned cropland of the FSU (Schierhorn et al. 2013; Kurganova et al. 2014). (Wertebach et al. in preparation) concluded that those global models overestimate the sequestration potential for Tyumen region, since most of the long-term abandoned fields are marginal sites with low carbon accumulation rates.

As agricultural LUI increases and decreases, the well-being of rural and urban population is simultaneously affected (Ioffe and Nefedova 2004; Ioffe 2005). Along with cropland abandonment in remote areas, whole farms and the respective villages of the sovkhoz' died (Prishchepov et al. 2012b). Between the need of qualified employees that are willing to work at agricultural enterprises and the ongoing trend of urbanisation, scenarios for attractive rural living have to be implemented in SLM strategies (chapter 2.2). Today, the Eurasian steppe region is getting more and more attractive for investments by international agro holdings (Petrick et al. 2013). Additionally, regional investments from the oil and gas industries in the northern part of Western Siberia return into the agricultural sector (Dronin and Kirilenko 2011). On one hand, this means improvements in quality of life for the rural population, but on the other hand presents more with risks for landscape functioning and biodiversity (Mueller et al. 2015).

Climate change adaptation and mitigation

Agriculture is sensitively affected by climate change but acts also as a major contributor to climate change. With a global share of 24 % from all GHG emissions, agriculture is the second largest contributor after the energy sector (FAO 2016a). 40 % of these agricultural emissions are directly related to livestock farming (enteric fermentation), another 27 % came from manure storage and utilisation as fertilizer and the remaining third is directly connected to arable farming (FAO 2016b). Thus, there is a strong interdependency between climate change adaptation and mitigation which has to be considered in SLM strategies. Western Siberia is known to have an outstanding climate change signal (Groisman and Soja 2009) and agricultural systems have to adapt to the shifting vegetation zones (Tchebakova et al. 2009; Kicklighter et al. 2014). Agricultural production in the Western Siberian grain belt has to cope with new growing conditions between increased heat stress and drought risks and beneficial effects of elevated atmospheric CO_2 levels. The net effect of these opposite impacts is still unclear and resilient cropping systems for the future have to integrate both directions. Current agricultural systems in Russia are extremely vulnerable, as demonstrated by the large crop shortfalls after the droughts in 2010 and 2012 (Kiselev et al. 2013). Alcamo et al. (2007) predicted a tripled risk of production shortfalls by the year 2070 without sound climate change adaptations in Russia. Sirotenko et al. (1997) evaluated a good chance for Russian agriculture to benefit from global warming with adequate adaptations but also pointed out catastrophic consequences for the business as usual scenario. In the holistic view, the consequences of climate change further affect humans (Lioubimtseva and Henebry 2009). Shifting ecozones may result in modified ecosystems and alternative land uses (Bergen et al. 2013). Lioubimtseva and Henebry (2012) highlighted that in terms of food security, also socio-economic interactions and feedbacks of weather extremes, as well as the environmental impacts of climate change need to be accounted for. Agricultural management strategies for the future have to include both climate change adaptation and mitigation aims in order to meet all three dimensions of sustainability.

Biodiversity preservation

Agricultural land-use intensity in Western Siberia is still moderate, compared to the intensive agricultural systems of Central Europe (chapter 2.1). The region is rich in high nature value areas and therefore biodiversity preservation is one key issue for SLM. Mathar et al. (2015) emphasised the positive effect of the diverse landscape mosaic across the forest steppe on species richness of vascular plants from a study in three test areas of 400 km² in Tyumen region. Weking et al. (2016) studied the effect of landscape elements and tillage intensity on species richness of *Orthoptera* (locusts) communities in the same test areas. They found the same positive influence of landscape elements as typical for the forest steppe. The current state of cultivated cropland and ex-arable land left unused for the last 25 years, seems to be a new steady state in terms of biodiversity conservation and carbon sequestration. Plant communities on theses ex-arable fields developed to a large degree in the direction of ancient grasslands, even though a complete recovery is unlikely (Kämpf et al. 2016c). In terms of the *Orthoptera* communities, Weking et al. (2016) found no differences in species richness and abundance between young ex-arable fields and ancient grassland. Not surprisingly, they all reported lowest species richness on cultivated cropland. However, all these findings indicate that there is a high potential to preserve a diverse agro-ecosystem on a vast extent in the south of Western Siberia. Therefore, the management of the agricultural system must show consideration of the surrounding ecosystems and landscape elements. On cropland, this means to reduce off-site damages through erosion control and proper use of agrochemicals (chapter 2.3 and 2.4). Establishing agricultural systems with a high agro-biodiversity, e.g. by introducing new crops (chapter 2.5) could further contribute to a balanced co-existence. Grassland management should be more integrated into the agricultural systems again, since moderate grazing or extensive mowing pressure is known to have positive feedback on the floral biodiversity (Dengler et al. 2014).

3.2 Cropping systems for sustainable dryland agriculture

The Western Siberian grain belt has been transformed by anthropogenic influence over the past centuries due its suitable conditions for settlements and arable farming (Mueller et al. 2015). Together with the large scale ploughing, soil degradation by erosion and unsustainable management occurred widespread across the region (Suleimenov 2006). NT technologies and the CA approach could help to make dryland agriculture in Western Siberia more sustainable (Derpsch et al. 2010; Mueller et al. 2015) and should become the dominant practice of the steppe regions (Suleimenov et al. 2015).

NT as contribution to CA

The best effect of NT can be achieved if it is implemented as one out of three factors within the CA system. During the 5-year SASCHA project, we could start to test the general suitability of NT under local conditions (chapter 2.3). We could also explore the possibilities to enhance the performance of soybeans by inoculation (chapter 2.5). The benefits of soybeans integrated in diverse crop rotations and the long-term effect of soil properties by continuous direct seeding are not detectable within the short period of our trials. Experiences from the literature reveal particularly under dry and rain-fed conditions of the continental climate zone highest potential of CA based on NT with the possibility to increase yields (Pittelkow et al. 2015). Whereas the global meta-analysis by Pittelkow et al. (2015) may have underestimated the potential of NT in dryland agriculture, the study of Kuhn et al. (2016) revealed more pronounced long-term benefits from NT experiments on the Chinese Loess Plateau. The positive yield effect is primarily related to the soil moisture savings by reduced tillage operations. Less tillage, however, means less mechanical weed regulation and is therefore usually connected to increased use of herbicides. The adverse effects on the environment by off-site damages and herbicide resistances are not negligible and have to be balanced in an overall evaluation (Farooq et al. 2011; Giller et al. 2015).

Crop rotations including pulses

The current cropping sequences in Western Siberia are often fallow-based and spring wheat dominated (Suleimenov 2006). The mechanical bare fallow year is sometimes used to apply organic manure or, to a very limited extent, to sow winter cereal crops that will follow (ROSSTAT 2016). Research findings from several field trials under comparable agro-climatic conditions revealed, that the bare fallow year can be substituted by legume crops without adverse yield effects on wheat (e.g. Suleimenov et al. 2010; Verburg et al. 2012; Machado et al. 2015). The early harvest date of pulses enables to sow winter cereals as following crops. Crop rotations that are more diverse will directly enhance agrobiodiversity but can also help to lower the weed pressure by switching between mono- and dicotyledonous species (FAO 2016c). The substitution of bare fallow by forage legumes is agronomically possible (Paroda et al. 2004), and will help with the integration of cropping and livestock systems and allow to spread organic manure during the vegetation period after cutting. This would increase the eco-efficiency, since the nutrient uptake by catch crops helps to avoid nutrient leaching into the groundwater.

Adapted fertilization strategies

During the transition to CA, the increased soil moisture enhances the fertilizer use efficiency as well, because of better mobility of nutrients in moist soils. Compared to Soviet times, we have already seen increased fertilizer efficiency in Russian agriculture (Liefert and Liefert 2012). As the total amount of fertilizer is applied in one dose during sowing like typical in dryland cropping, the use of stabilised fertilizers is very promising. Most of the market-available slow-release fertilizers are based on chemical delaying and/or coatings out of organic compounds. Those have themselves also possibly adverse effects on the agro-ecosystem (Scheurer et al. 2016). An environmentally friendly approach with inorganic coating of urea fertilizer failed in our field trials, possibly due to poor coating quality (chapter 2.4). In this field, some more fundamental research on the short-term behaviour is necessary to enhance the production process. In terms of organic fertilization, there is also large potential for improvements. Average transport distances for manure are about 5 to 10 km around the stable/storage – on farms with some 1000 ha cropland and average field sizes of 100 ha. Under current price levels for mineral fertilizer and ordinary machinery equipment, transport distances up to 25 km are profitable. With some investments in better transport and spreading technology the profitable transport distance could be expanded up to 45 km (Störrle et al. 2015). The organic fertilization would, furthermore, help to improve the presently partial poor soil structure on arable fields in Tyumen region (Störrle et al. 2016), particularly in conjunction with reduced tillage.

Further improvements

The performance of regionally-bred varieties as well as the seed quality are comparatively poor in the Western Siberian grain belt (Suleimenov et al. 2015). Multinational seed companies have little interest in investing in the breeding of regional adapted varieties, since reproduction up to 10 years is common on Siberian farms. The responsibility for plant breeding still lies with the universities and federal research institutes, which often suffer deficits in technology (Suleimenov et al. 2015). On the contrary, the usage of certified seed quality is already being implemented in Kazakhstan (Lioubimtseva and Henebry 2012). Farooq et al. (2011) explicitly request breeding of varieties adapted to CA, what is after Trethowan et al. (2012) possible. The need of special plant breeding for CA can be ascribed to an often observed genotype × tillage practice interaction (Serraj and Siddique 2012).

Integration of livestock

As mentioned in chapter 2.1and 2.2 as a finding from the LUI analysis, SLM has always to follow a holistic view and cannot be separated into arable and livestock farming. Resilient agricultural systems are known as cropping systems with integrated livestock. According to the Russian traditions of a strict separation between the veterinary and agronomy, the consideration of manure in crop production is still very poor. Störrle et al. (submitted) estimated a high potential of improved manure management in Tyumen region, both for minimising leaching from storage and maximising the fertilizer benefit in crop production.

The close connection between arable farming and regional animal fattening has also gained importance, since the export of the produced grain is very limited. Therefore, all benefits of an integrated agricultural system should be utilised, including transporting and spreading the organic manure as valuable fertilizer. The integration of grazing livestock, mainly ruminants, is particularly important in terms of biodiversity preservation. On the one hand moderate grazing pressure is known to be beneficial for floral biodiversity on grassland and abandoned fields (Kraemer et al. 2015). On the other hand, forage legumes are good fodder for ruminants and contribute with a high preceding crop effect beneficial to diverse crop rotations. Altogether, the CA approach for Western Siberia has to be supplemented by the integration of moderate livestock farming to become a comprehensive SLM strategy.

Lacking implementation of CA in Western Siberia

CA is practised widely across regions with similar agro-climatic conditions to the Western Siberian grain belt like the Northern Great Plains or the cold north of Kazakhstan (Derpsch and Friedrich 2009). The question, however, of why CA is barely implemented in Western Siberia still remains. Whereas in Kazakhstan governmental support is especially focused on CA technologies (Kienzler et al. 2012), in Western Siberia all machinery still qualifies for the same subsidies. In Tyumen region nearly no specific NT seed drill was sold during the last years, in Chelyabinsk only few (Krasnoborov 2016). The best adoption can be found in Altai krai (Grunwald et al. 2015), where the soil moisture deficit is the largest across the Western Siberian grain belt. Besides support in technology, better seed quality is also available and commonly used in Kazakhstan, which contributes to the advantageous yield effect (Lioubimtseva and Henebry 2012). Furthermore, the Kazakh grain production is one of the major export goods. The products of the Western Siberian grain belt is mainly consumed locally, since global trading is difficult because of the long distance to the next harbours (more than 3000 km either east or west). Another reason for the lack of implementation despite the general suitability of CA in Siberian dryland cropping systems could be the spatial proximity to the financially-sound oil and gas industries in the northern autonomous regions (Yu et al. 2015). Regional reinvestments into agriculture could influence the marginal returns and decouple crop production from natural yield potential. Beyond economics, farm managers as well as politicians in Western Siberia may still have some reservations against the ‘western’ CA system, since most of them were socialised and educated during Soviet times (Suleimenov 2006; Wall et al. 2007). However, this cannot explain differences to Kazakhstan. The driver for the gap of CA adoption in Western Siberia has to be seen as the unique combination of these socio-economic motives.

3.3 Limits and trade-offs of Sustainable Intensification

Within the multi-layered and lively discussions about the names and meanings of SI and EI, Tittonell (2014) asked the following questions: "Can intensification be sustainable without being ecological or eco-efficient" and "Is ecological intensification always sustainable?" He concluded from the current state of agricultural intensification, which is neither socially nor thermodynamically sustainable, that consequently this intensification could not be ecological or eco-efficient (Tittonell 2014). Much of the debate on the words themselves is related to the differences between western large scale agriculture and small-holder farming in developing countries (Godfray 2015). The observed damages to the environment, biodiversity losses and failures to reach the zero-hunger goal necessitate an applied dimension of SI with regionally modified strategies. Beyond all the criticism of the limits and missing clarity in the definition of SI, Giller et al. (2015) emphasised the need for locally adapted agronomic capacity building. Following their idea of a 'systems agronomy', SI is more than adapting principles or technologies but explicitly calls attention to social acceptability. The agricultural subproject of the SASCHA project aimed at an applied SI approach. Together with local scientists, farm managers and machinists, some well-known ideas were jointly performed under practical conditions in Western Siberia. Therefore, the novel aspect was not the result of higher soil moisture under NT but the first step to convince the farmers of managing their fields conservational and against traditions. The trials and studies on different spatial scales that are presented in this thesis can be seen as contributions to SLM strategy based on applied SI.

We depicted some possible pathways to shape agriculture in Western Siberia more sustainably. Against the background of the forest steppes' peculiarities and the unique land-use history in the study region, a combination of SI on arable land and a moderate grazing regime on grassland and older abandoned fields seems to be the best combination. This does not necessarily mean a clear preference for 'land-sparing' over 'land-sharing'. The increasing attention to multiple interactions and interdependencies between agricultural and near-natural ecosystems helped to overcome the old and strict division between 'sharing' and 'sparing' (Tscharntke et al. 2012). Arable fields across the Western Siberian grain belt are, due to their large extent, highly suitable for precision farming technologies. One field could be managed in adapted intensity according to small-scale differences in soil physical and chemical properties, based on GPS navigation. This technology is market-available in Russia and some large farms have already installed it in tractors – but to date, it is used mainly for observing working time and fuel consumption. Implementation of site-specific intensity levels would be a kind of 'land-sharing' within the arable field. Thus, smooth transitions between 'sharing' and 'sparing' may be achieved and could possibly see both during the course of SI on a single field.

The approach of applied SI by promoting conservation agriculture based on NT for the Western Siberian grain belt is related to the negative concomitant effect of increased herbicide applications. The success of CA is largely based on the pre-sowing application of total herbicides, mainly glyphosate (Giller et al. 2015). Current findings about the possible impacts of glyphosate on humans and all ecosystems require discussions about future cropping systems without boundaries. After a phase of increasingly reduced agronomic practise, a re-thinking of all agronomic instruments is necessary. Diverse crop rotations including legumes that are adapted to changing climate conditions would be a base for resilient cropping systems with a reduced reliance on a single herbicide.

However, who is able to evaluate the positive effects of soil moisture saving or erosion prevention against the adverse pollution by pesticides? The concept of ecosystem services attempts this, but particularly the approach of monetarising the services stands in contrast. Moreover, the use of GMO is often understood as an important contribution to SI, but the large-scale examples from the Americas demonstrated the vulnerability of such systems in terms of emerging herbicide resistances. In summary, no system is without barriers, but for the Western Siberian grain belt there is a great chance to stay as a big contributor in environmentally-friendly crop production if SLM strategies are implemented.

Chapter 4
Conclusion

Overall conclusion

The Western Siberian grain belt is a region of global significance in terms of agricultural production as well as for ecosystem services and biodiversity preservation. Politically induced land-use change is a tradition in this region, extending back to Khrushchev's Virgin Lands Campaign and the enormous farmland abandonment after the dissolution of the Soviet Union. So far, agricultural land-use intensity is – compared to Central Europe – relatively low and therefore a promising starting point for sustainable land management strategies.

From the history of agricultural land use, we derived capacity limits for cropland and grassland usage on landscape scale. Based on this knowledge, the need of individual strategies for the two land-use types cropland and grassland became obvious. The increasing intensity on cropland needs to be shaped sustainably. The negative impacts on biodiversity through decreasing grassland intensity could be prevented by incentives for moderate grazing systems.

Especially considering the effects of climate change, agronomic strategies for sustainable land management revealed promising advantages when changing the cropping systems to conservation agriculture. One possibility to increase eco-efficiency in dryland cropping of Western Siberia was confirmed in field trials with spring wheat: it was possible to harvest at least the same yield with no-till compared to conventional tillage. These results were derived from above-average cold and wet experimental years – opposed to the climate change predictions of warmer and drier growing seasons. Under ongoing global warming, higher average yields as well as stable yields in extreme years are likely, according to the literature. The greatest advantage of sustainable intensification by no-till in dryland cropping systems is possible, if it is implemented in the complete system of conservation agriculture with permanent residue cover and in diverse crop rotations. The currently common fallow years in cropping systems of the Western Siberian grain belt could be beneficially substituted by legume crops. Soybeans are a promising new crop for this region experiencing shifting vegetation zones caused by climate change. Particularly, if the seeds are inoculated with soy-specific rhizobia bacteria they can contribute to resilient and sustainable crop rotations and thereby enhance both agro-biodiversity and eco-efficiency. Among all C3 crops, legumes like soybeans can best utilise the elevated CO_2 concentrations resultant of global warming. Thus, the importance of pulses in sustainable dryland cropping systems will increase. Preserving soil moisture by practising direct seeding techniques also increases nutrient use efficiency, due to better mobility to the plant roots. Against this background, improved fertilizer strategies are of interest, e.g. by using slow-release fertilizers to supply the plants at optimal growth stages. A promising and environmentally-friendly approach with mineral coating of urea to delay the nutrient release was tested on field scale. After one experimental year, no clear effects to improve eco-efficiency were observed. The laboratory scale production of the novel fertilizer needs further improvements to ensure good coating quality. All these findings are examples for applied sustainable intensification and can contribute to sustainable land management strategies on different spatial scale.

The focus of this work was on agronomic strategies under changing climate conditions. Nevertheless, the integration of livestock and arable farming is crucial for sustainable agriculture. The agricultural system of the Western Siberian grain belt can considerably benefit from crop-livestock integration which will lead to: better soil fertility and efficient nutrient management, increased ecosystem services and biodiversity, and added value independent from export markets. However, the current trends of intensifying cropland management request main attention of a sustainable shape of Siberian dryland cropping systems.

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Summary

The growing global population and the ongoing loss of arable soils increase the pressure on agricultural production. In conjunction with climate change, this causes new challenges for agricultural production systems worldwide and requires a more sustainable approach for the future. The concept of 'sustainable land management' (SLM) is known as a concretisation of the sustainable development goals in the field of agriculture. The Western Siberian grain belt covers 1 million km² in Asiatic Russia and is of global importance for agricultural production as well as an important carbon sink and of international interest for biodiversity preservation.

The work was conducted as part of the interdisciplinary German-Russian SASCHA project, which focused on SLM strategies at the intersection of climate change and land-use change in Tyumen region of Western Siberia. The objective of this work was to identify strategies for sustainable agricultural land management in Western Siberia with a focus on arable farming issues. Therefore, specifically the following research questions were addressed: (i) What does the history of agricultural land use across the Western Siberian grain belt tell us for developing future strategies? (ii) How can the eco-efficiency of Western Siberian cereal cropping systems be increased under the strain of changing climatic conditions? (iii) Is soybean cultivation capable of diversifying crop rotations in the southern part of Western Siberia?

Triggered by the dissolution of the Soviet Union and the collapse of the state farm system, massive land-use changes took place in the region. A normalised input-oriented intensity index was developed to quantify these changes and patterns in land-use intensity (LUI). Based on subnational, annual statistical data, two separate indices for cropland and grassland were calculated and applied on two spatial scales (provinces and districts). The spatio-temporal analysis showed significant opposite trends: decreasing intensity on grassland by -0.015 LUI units per year and intensification on cropland by +0.014 LUI units per year. The land-use changes that accompanied the post-Soviet transition from a planned to a market-driven economy also implied substantial socio-economic consequences for agricultural production. Based on the LUI analysis, locally adapted SLM scenarios were developed for Tyumen province and priority areas for implementation were identified. The findings clearly showed the need for having a different SLM strategy 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. Two major strategies were derived for the Western Siberian grain belt: low-intensity grazing for grassland conservation and sustainable intensification (SI) on cropland instead of cropland expansion.

The system of conservation agriculture is a known possibility for SI in dryland cropping systems. Particularly under climate change predictions of drier and warmer growing conditions, no-till farming could be a promising way to increase eco-efficiency in Western Siberian cereal production systems. Therefore, a full-factorial split-split-plot field trial was conducted on a farmer's field to test adaptations of tillage (usual conventional tillage 'CT' vs. no-till 'NT'), seeding depth (usual deep 6.5 vs. shallow 4.5 cm) and seeding rate (usual high 600 vs. reduced 450 grains m^{-2}) for the potential to increase water use efficiency and grain yield. Results from two above-average wet and cold growing seasons showed significantly better soil water storage of NT (+40 %) and no adverse effect on spring wheat grain yield and grain quality. Impacts of variations in seeding rate and seed placement were less pronounced. The highest yields of 3.19 and 3.82 t ha^{-1} were observed with NT treatment in 2014 and 2015, respectively.

Other alternatives implemented to increase eco-efficiency of dryland cropping systems are enhanced fertilizer strategies. In Western Siberia, nitrogen (N) fertilizers (urea or ammonium-nitrate 'Selitra') in cereal production are commonly banded during sowing directly into the seed furrow. The performance of a new kind of slow-release fertilizer was tested in a field trial under on-farm conditions. A modified urea with silicate coating and urease inhibitor was compared in four N-levels (25/50/75/100 %) to 100 % of conventional urea, 100 % of Selitra and an unfertilized control in RCBD. Results showed significant differences in soil nitrate availability but no differences in ammonium release and

no significant impact on grain yield or quality. From the results of this field trial there seemed to be no beneficial advantage of the tested novel slow-release fertilizer so far. More field site years and further improvements of the laboratory-scale fertilizer production are needed for scientifically founded results.

Climate change is likely to considerably affect future growing conditions in regions around the current high-latitude boundaries of agricultural production. Specifically for soybeans, this leads to a northwards shift of the northernmost limit for cultivation. Therefore, the effect of soybean seed inoculation with *Bradyrhizobium japonicum* was investigated in comparison to an untreated control in a small-scale split-plot field trial under high latitude conditions. Leaf chlorophyll content by SPAD-meter readings was used as proxy for biological nitrogen fixation. Inoculation was always successful, since nodulation took only place in plots with seed treatment. Effect sizes of SPAD-values were significantly positive at beginning of seed filling but did not differ earlier. Except for the warmest site year, inoculation had no impact on seed yield and protein yield. Under cold growing conditions of high latitude regions, temperature sums seemed to limit soybean yield and the effectiveness of inoculation with *B. japonicum*. To implement soybeans as legumes in crop rotations, nevertheless, inoculation is mandatory, since soils in high latitudes lack soy-specific rhizobia bacteria.

The trials and studies compiled in this thesis are examples of contributions to SLM strategies on varying spatial and temporal scales. Besides all the promising benefits of the described SI applications, some drawbacks must be considered: NT and CA often result in increased herbicide applications, genetically modified varieties (GMO) and herbicide resistances. Diverse crop rotations including legumes, however, would be a base for resilient cropping systems with a reduced reliance on a single herbicide. Moreover, Western Siberia has a great potential to become a key contributor to non-GMO dryland cropping.

Even though the focus of this thesis was on agronomic strategies, the integration of livestock and arable farming is crucial for sustainable agriculture. The agricultural system of the Western Siberian grain belt could considerably benefit from crop-livestock integration by better soil fertility and enhanced nutrient management. The current observed trend of cropland intensification, however, will require increased attention paid to the sustainability of Siberian arable farming. Considering the forest steppes' peculiarities and the unique land-use history, SI implemented on cropland and a moderate grazing regime on grassland seems to be the best combination for SLM across the Western Siberian grain belt.

Zusammenfassung

Die wachsende Weltbevölkerung und der fortschreitende Verlust an Ackerboden erhöhen den Druck auf die landwirtschaftliche Produktion. In Kombination mit den Auswirkungen des Klimawandels steht die Landwirtschaft weltweit vor neuen Herausforderungen, die nur mit nachhaltigen Ansätzen gelöst werden können. Das Konzept ‚Nachhaltiges Landmanagement' (SLM) konkretisiert diese Ziele im Bereich der Landwirtschaft. Der westsibirische Getreidegürtel erstreckt sich über 1 Millionen km^2 im asiatischen Teil Russlands und ist von globaler Bedeutung für die Agrarproduktion sowie als Kohlenstoffsenke und zum Biodiversitätsschutz. Zielsetzung dieser Arbeit war die Identifikation von nachhaltigen landwirtschaftlichen Nutzungsstrategien in Westsibirien mit einem Fokus auf ackerbauliche Maßnahmen. Dazu wurden im Detail folgende Forschungsfragen formuliert: (i) Welche angepassten Zukunftsstrategien lassen sich aus der historischen Landnutzung ableiten? (ii) Wie lässt sich die Ökoeffizienz von Getreideproduktionssystemen unter den Auswirkungen des Klimawandels erhöhen? (iii) Eignen sich Sojabohnen dazu, die Fruchtfolgen im Süden Westsibiriens zu diversifizieren? Die Studien fanden im Rahmen des interdisziplinären, deutsch-russischen SASCHA-Projektes statt, welches sich mit SLM-Strategien an der Schnittstelle zwischen Landnutzungs- und Klimawandel im Tjumener Gebiet in Westsibirien beschäftigt hat.

Die Auflösung der Sowjetunion und der Zusammenbruch der staatlichen Landwirtschaft verursachten einen massiven Landnutzungswandel in dieser Region. Um diese Änderungen in räumlichen Mustern und zeitlicher Dimension zu quantifizieren, wurde ein normalisierter, input-orientierter Landnutzungsintensitätsindex (LUI) entwickelt. Basierend auf jährlichen, regionalen Statistikdaten wurden zwei getrennte Indizes für Ackerland und Grünland berechnet und auf zwei räumlichen Skalen (Provinz, Distrikt) angewendet. Diese raum-zeitliche Analyse zeigte signifikante, gegenläufige Entwicklungen: Extensivierung auf Grünland von −0.015 LUI Einheiten pro Jahr und Intensivierung auf Ackerland von +0.014 LUI Einheiten pro Jahr. Die mit der Transformation von Plan- zur Marktwirtschaft einhergehenden Landnutzungsänderungen beeinflussten auch maßgeblich die sozio-ökonomischen Rahmenbedingungen der Landwirtschaft. Ausgehend von der LUI-Analyse konnten lokal angepasste SLM-Strategien entwickelt und Vorranggebiete zur Umsetzung dieser Szenarien identifiziert werden. Die Ergebnisse zeigten eindeutig die Notwendigkeit von unterschiedlichen Strategien auf Grünland (überwiegend als Allmende Weide von ländlichen Haushalten genutzt) und Ackerland (überwiegend von großen Agrarbetrieben bewirtschaftet). Für den Westsibirischen Getreidegürtel wurden zwei übergeordnete Strategien abgeleitet: extensive Beweidung zur Grünlanderhaltung und nachhaltige Intensivierung (SI) auf bestehendem Ackerland anstelle von Ackerflächenexpansion.

‚Conservation Agriculture' (CA) ist als System bekannt, das im Trockenfeldbau Potential zur SI bietet. Insbesondere unter den prognostizierten Klimawandeleffekten von trockeneren und wärmeren Wachstumsbedingungen ist Direktsaat (no-till, NT) eine vielversprechende Option zur Erhöhung der Ökoeffizienz im westsibirischen Getreideanbausystem. Dazu wurde ein vollfaktorieller Feldversuch im Split-split-plot-Design unter on-farm Bedingungen durchgeführt, um Anpassungen von Bodenbearbeitung (üblich konventionell CT vs. Direktsaat NT), Aussaattiefe (üblich tief 6.5 vs. flach 4.5 cm) und Aussaatstärke (üblich viel 600 vs. reduziert 450 Körner m^{-2}) hinsichtlich Wassernutzungseffizienz und Kornertrag zu prüfen. Ergebnisse von zwei überdurchschnittlich kalten und nassen Versuchsjahren zeigten signifikant höhere Bodenwassergehalte unter NT (+40 %) und keine negativen Effekte auf Sommerweizenertrag und -qualität. Die Einflüsse von veränderten Saatstärken und Ablagetiefen waren geringbedeutend. Höchste Erträge wurden mit 3.19 und 3.82 t ha^{-1} (2014 bzw. 2015) jeweils in NT Varianten erzielt.

Eine weitere Option zur Steigerung der Ökoeffizienz im Trockenfeldbau ist eine Verbesserung der Düngestrategie. In Westsibirien wird Stickstoff (N) (überwiegend als Harnstoff oder Ammonium-Nitrat ‚Selitra') typischerweise als Unterfußdüngung während der Saat ausgebracht. In einem Feldversuch wurde die Wirksamkeit eines neuartigen geschützten Harnstoffdüngers mit Langzeitwirkung unter Praxisbedingungen untersucht. Dazu wurde der mit Silikat-Ummantelung und Urease-Hemmstoff modifizierte Harnstoff in vier N-Stufen (25/50/75/100 %) mit 100 % herkömmlichen Harnstoff,

100 % Selitra und einer ungedüngten Kontrolle verglichen. Die Ergebnisse zeigten signifikante Unterschiede in der Nitratverfügbarkeit aber weder unterschiedliche Ammoniumfreisetzungen noch Effekte auf Kornertrag oder -qualität. Zur abschließenden Beurteilung fehlen jedoch weitere Versuchsjahre sowie eine Verbesserung des Produktionsprozesses.

Insbesondere an der nördlichen Ausdehnungsgrenze der landwirtschaftlichen Nutzung sind gravierende Auswirkungen des Klimawandels auf die Wachstumsbedingungen zu erwarten. Für Sojabohnen führt das zu einer Nordwärts-Verlagerung der Anbaugebiete. Daher wurde der Effekt einer Saatgutimpfung mit *Bradyrhizobium japonicum* im Vergleich zur unbehandelten Kontrolle an mehreren frühreifen Sorten in einem kleinskaligen Feldversuch in nördlichen Breiten untersucht. Der Blattchlorophyllgehalt, gemessen als SPAD-Wert, wurde dabei als Indikator für die Luftstickstofffixierung herangezogen. Die Impfung war immer erfolgreich, da nur behandelte Pflanzen Knöllchen ausbildeten. Die Effektstärken der SPAD-Werte waren signifikant positiv zu Beginn der Samenentwicklung, jedoch ohne Unterschiede in früheren Wachstumsstadien. Außer im wärmsten Versuchsjahr hatte die Impfung keine Auswirkung auf Bohnen- und Proteinertrag. Unter den kalten Wachstumsbedingungen hoher nördlicher Breiten schien die Temperatursumme den Sojaertrag und die Effektivität der Impfung zu limitieren. Um Soja als Leguminose in Fruchtfolgen zu integrieren ist die Impfung jedoch zwingend notwendig, da in Böden höherer Breiten natürlicherweise keine soja-spezifischen Bakterienstämme vorhanden sind.

Die in dieser Arbeit zusammengestellten Versuche und Analysen sind Beispiele für Beiträge zu SLM auf verschiedenen räumlichen und zeitlichen Skalenebenen. Neben den vielversprechenden Vorteilen der beschriebenen Optionen der angewandten SI, müssen jedoch auch einige negative Begleiteffekte berücksichtigt werden: NT und CA bedingen häufig höhere Herbizid Einsätze, gentechnisch veränderte (GVO) Sorten und Herbizidresistenzprobleme. Abwechslungsreiche Fruchtfolgen mit integrierten Leguminosen eröffnen jedoch eine Perspektive für widerstandsfähige Trockenfeldbausysteme ohne Abhängigkeiten von einzelnen Herbiziden. Darüber hinaus hat Westsibirien die große Chance einen bedeutenden Beitrag im GVO-freien Trockenfeldbau zu leisten.

Auch wenn pflanzenbauliche Strategien im Fokus dieser Arbeit standen, ist auch in Westsibirien die Integration von Viehhaltung und Ackerbau unerlässlich für eine nachhaltige Landwirtschaft. Insbesondere durch besseres Nährstoffmanagement und erhöhte Bodenfruchtbarkeit könnte das westsibirische Agrarsystem erheblich von integrierten Betriebskreisläufen profitieren. Die fortschreitende Intensivierung in der Ackernutzung erfordert allerdings eine erhöhte Aufmerksamkeit für nachhaltige Pflanzenproduktion. Vor dem Hintergrund der Besonderheiten der Waldsteppe und der einmaligen Landnutzungsgeschichte erscheint eine nachhaltige Intensivierung bestehender Ackerflächen und extensive Beweidung auf Grünland als ideale Kombination für nachhaltige landwirtschaftliche Nutzungsstrategie im Westsibirischen Getreidegürtel.

Acknowledgements

In the beginning, I would like to thank those crazy people, who sat together with the idea to start a project in Russia. The first idea developed into the fascinating SASCHA project and was a great deal for many young scientists – and I was a lucky one of those who have been infected with the ‘Russia Virus’.

Deepest thanks to my supervisors! First, I want to thank Dieter Trautz, that he trusted me to fulfil the job at the University of Applied Sciences Osnabrück. I was happy to share many Siberian experiences with him: hot negotiations, joint harvest fieldwork, road trips with many agronomic on-site discussions or simple village life. Furthermore, I very much appreciated the high level of self-responsibility. Secondly, I would like to thank Gabriele Broll that she became my supervisor at the cooperating Osnabrück University. She always encouraged my approaches and supported me to strengthening my research profile. Especially the very structured questions and comments on the drafts and manuscripts helped a lot to improve my work. Finally yet importantly, I have to thank my former supervisor Nicola Fohrer that she agreed with my change from Kiel to Osnabrück.

During the project, I had a lot of helping heads and hands, especially with the fieldwork in Russia. I would like to thank my colleague and friend Dmitry Redozubov for a fantastic joint trial season, fruitful scientific discussions, daily life assistance in Ishim’s prison quarter and so many happy moments. Nina Bome was always supporting our soybean activities, thanks to her for all the issues related to Biostation Kuchak as well as the feeling to be a member of the Biofak’s family. Roman Latyntsev as well as Anton I would like to thank a lot for uncomplicated support with mobility, I will always remember every single kilometre with the lovely Niva. I was happy that every year some students engaged the Siberian adventure, some as internship but most to write their thesis. Thanks to Annemarie Trame, Male Bokelmann, Sontka Nülle, Jens Kampschulte, Christian Jeismann and Jennifer Nickel for help in the field and for welcome changes in lonely Ishim evenings. Special thanks to Alison Simerly for the quick and helpful English language check.

No project without funding – in this sense I am grateful for the financial support of the SASCHA project by BMBF. However, without additional support by Amazonen-Werke H. Dreyer GmbH & Co. KG, namely Viktor Buxmann and Andrey Krasnoborov, and Agroholding Yubileyny, namely Sergey and Nikolay Mamontov, the field trials would not have been possible. Thanks for all the straightforward solutions with machinery, fields, drivers, spare parts, accommodation etc. – I deeply acknowledge all that effort. In this context, I would also like to mention the help of Natalya Stupak and Andrey Ermakov to come in contact with Yubileyny enterprise.

Beyond the work, a project always consists of people and I want to thank all SASCHA colleagues for the great common moments in Siberia. Special thanks to Immo for his friendship, always interesting discussions, sharing my Plattenbau flat in Ishim, hard-core paper writing in Denmark and various coffee breaks in Osnabrück. I would like to thank all current and former SASCHA members from UAS Osnabrück - Kathrin Kiel, Hubertus von Dressler, Gerhard Clemens, Yuliana Griewald, Sandra Fleischer and Philipp Kues – for the family atmosphere at the faculty.

Furthermore, my working group in HH building helped me to survive during the winters in Osnabrück: thanks to Carl, Matthias and Hanna for sharing the PhD challenges and all other colleagues for all the joint meals, nice talks in the kitchen and creative ideas.

I was extremely happy to share one Siberian summer with my son Sören. I hope that he mainly remembers these beautiful moments and will forget the deprivations soon.

Finally, I would like to express my happiness about the bright star that I saw once at the Siberian night sky. It remained always visible in my mind and led me into the right direction, even if there were some obstacles to overcome.

Appendix

List of Publications

– peer reviewed publications –

Kühling I, Hüsing B, Bome N and Trautz D (2017): Soybeans in high latitudes: effects of Bradyrhizobium inoculation in Northwest Germany and southern West Siberia. Org Agr 1–13. doi: 10.1007/s13165-017-0181-y.

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Kühling I, Trautz D, Langsenkamp F (2017): Bildanalytische Farberkennung zur Geschwindigkeitsregulierung beim Jäteflieger im ökologischen Möhrenanbau. Beiträge zur 14. Wissenschaftstagung Ökologischer Landbau (*accepted*).

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Curriculum Vitae

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