Supplementary Information

Influence of high-latitude warming and land-use changes on the early 20th century northern Eurasian CO2 sink

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Supplementary Methods

GOSKOMSTAT cropland area statistics

National statistics were provided for the Russian Empire during the pre-Soviet period starting from 1913 and the Former Soviet Union (FSU) during the period 1917-1961 (before FAOSTAT compilation). The data was compiled from the archived paper-based books of statistics in Russian. Official data for 1941-1945 (corresponding to total duration of the WWII) have been published with griffon "confidential" back in 1959 but became available for the general public in 1990 by the end of the Perestroika. The data for Russian Empire is presented in its actual borders, i.e. not conform to FSU borders, and originally derived in obsolete Russian units of land area (dessiatina, 1 Des=1.09 ha). At the time of the Soviet Union, the statistics provided total cropland area (million ha), and cropland area in each of the 15 Federal Republics (thousands ha). Even though the borders of the Russian Empire and FSU differ, both covered the areas which account for most of the cropland area (Russia, Ukraine, Kazakhstan) and therefore we aggregate both datasets.

The official records provided values of area of winter and spring crops, industrial crops and sown area for fodder. Total cropland area for the FSU aggregated for all types of agriculture products (hereafter referred to simply as LU_{NEW}) from these sources is shown in Figure **S1**. When available in the official records, we collected data for the different regions (former republics) composing FSU. We also present data for occupied and non-occupied territories during the World War II (1941-1945, Supplementary Data), even though these values have gaps during the peak of occupation (1941/42). It should be noted that the collected values during WWII might suffer from discrepancies due to the difficulty in reporting data for the conflict areas. In order to further evaluate how LU_{NEW} captures the transitions that occurred in FSU during the first half of the 20th century, we compare them with several socio-economical statistics, described in the main manuscript.

The full list of references is provided in Supplementary References section and the dataset is provided in Supplementary Data.

Producing new spatially-explicit maps from GOSKOMSTAT and LUH1 data

In order to simulate the resulting changes in C-stocks from LU_{NEW} using ORCHIDEE-MICT, spatially-explicit maps need to be derived. Here we preserve the main geographical distribution of cropland while correcting for the updated values in LU_{NEW}, as performed in previous works (e.g. Vuichard et al. (2008)). The procedure is described in detail below.

First we fill the two missing years (1918 and 1919) using a linear adjustment. Then, for each time-step (i.e. every year), we calculate the total difference in cropland area (A_c) between LU_{REF} and LU_{NEW}:

$$\Delta A_C = A_{C-REF} - A_{C-NEW}$$

Since LU_{NEW} data estimates lower cropland area than LU_{REF}, ΔA_C is always positive. This difference is distributed among all pixels ($\Delta A_{C(i,j)}$), proportionally to their corresponding fraction of the total crop area in LU_{REF}:

$$\Delta A_{C(i,j)} = A_C \times \frac{A_{C-REF(i,j)}}{A_{C-REF}}$$

We then produce new maps by subtracting the pixel-weighted difference in crop area between the two datasets from the two crop PFT types in LU_{REF}, proportionally to their corresponding pixel fraction ($PFT_{C(i,j,pft)}$):

$$A_{C-NEW(i,j,pft)} = A_{C-REF(i,j,pft)} - \Delta A_{C(i,j)} \times fPFT_{C(i,j,pft)}$$

Therefore, more cropland area is reduced in pixels with high cropland area in LU_{REF}, which allows preserving the main geographic patterns of cropland distribution in the territory. The country-level cropland area data collected from national statistics was then compared with the crop area represented in LU_{REF} and the updated maps (LU_{NEW}), shown in Figure **S7**.

The area removed from crop PFTs is then assigned to natural vegetation PFTs. Given that we have no additional information about forest or grassland changes in FSU during this period (apart from LU_{REF} spatial patterns, Figure **S1**), we define two scenarios for the type of natural vegetation growing in the crop area after abandonment.

In the first one, $\Delta A_{C(i,j)}$ is assigned in priority to the forest PFTs already present, otherwise it is replaced by grassland (FOR scenario). The second scenario (GRA) is similar, but with grassland PFTs replacing $\Delta A_{C(i,j)}$ if grassland is already present, and otherwise allocated to forests.

$$\text{FOR} = \begin{cases} A_{F-NEW(i,j,pft)} = A_{F-REF(i,j,pft)} + \Delta A_{C(i,j)} \times PFT_{F(i,j)}, & A_{F-REF(i,j,pft)} > 0 \\ A_{G-NEW(i,j,pft)} = A_{G-REF(i,j,pft)} + \Delta A_{C(i,j)} \times PFT_{G(i,j)}, & A_{F-REF(i,j,pft)} = 0 \end{cases}$$

$$\text{GRA} = \begin{cases} A_{G-NEW(i,j,pft)} = A_{G-REF(i,j,pft)} + \Delta A_{C(i,j)} \times PFT_{G(i,j)}, & A_{G-REF(i,j,pft)} > 0 \\ A_{F-N\square W(i,j,pft)} = A_{F-REF(i,j,pft)} + \Delta A_{C(i,j)} \times PFT_{F(i,j)}, & A_{G-REF(i,j,pft)} = 0 \end{cases}$$

where A_F and A_G correspond to forest and grassland area respectively. It should be noted that these two cases correspond to the two extremes of the possible range of forest vs. grassland trajectories in regions where agricultural area was abandoned. The resulting total forest and grassland areas over FSU corresponding to each case are shown in Figure **S3**.

Since cropland area is updated proportionally to the contribution of each pixel to the FSU total, most crop areas abandoned are in the western regions (Figure **S1**), reproducing the dynamics reported in the literature. When comparing with collected country-level statistics (Figure **S8**), the resulting updated cropland area for each country therefore results in a better match to reported cropland extent than LU_{REF}, especially in the FSU regions contributing more for the total farmland.

The method used here to update LUC maps does not account explicitly regional dynamics, such as the displacement of farmland from the front and occupied regions during WWII to the eastern countries (Linz, 1984). We deliberately did not account for this displacement, as it would imply changing also natural vegetation fractions in other regions of the FSU (e.g. require forest/grassland removal), and increase the possible inconsistencies between the datasets. Even though we update our land-cover maps based solely on the geographical distribution of vegetation from LU_{REF} (similar to Vuichard et al. (2008)), our data still provides a better match to country-level estimates of crop area (Figure **S8**) than previous reconstructions.

Supplementary Tables

Table S1 - In standard ORCHIDEE-MICT (Guimberteau et al., 2017) crop parameters are based on recent observations and are therefore representative of present-day productive crop varieties. Since we are mainly interested in the earlier half of the 20th century, we adjusted the crop the maximum rate of carboxylation (Vc_{max}) for lower values, calibrated against observations from several cropland sites. The two tropical PFTs also used in ORCHIDEE-MICT are not present in the study region, and thus not considered.

PFT	Vc_{max} (micromol.m^{-2}.s^{-1})
Temperate needle-leaf evergreen trees	45
Temperate broad-leaf evergreen trees	45
Temperate broad-leaf deciduous trees	55
Boreal needle-leaf evergreen trees	45
Boreal broad-leaf deciduous trees	45
Boreal needle-leaf deciduous trees	35
C3 natural grass	55
C4 natural grass	25
C3 crops	50
C4 crops	40

Supplementary Figures

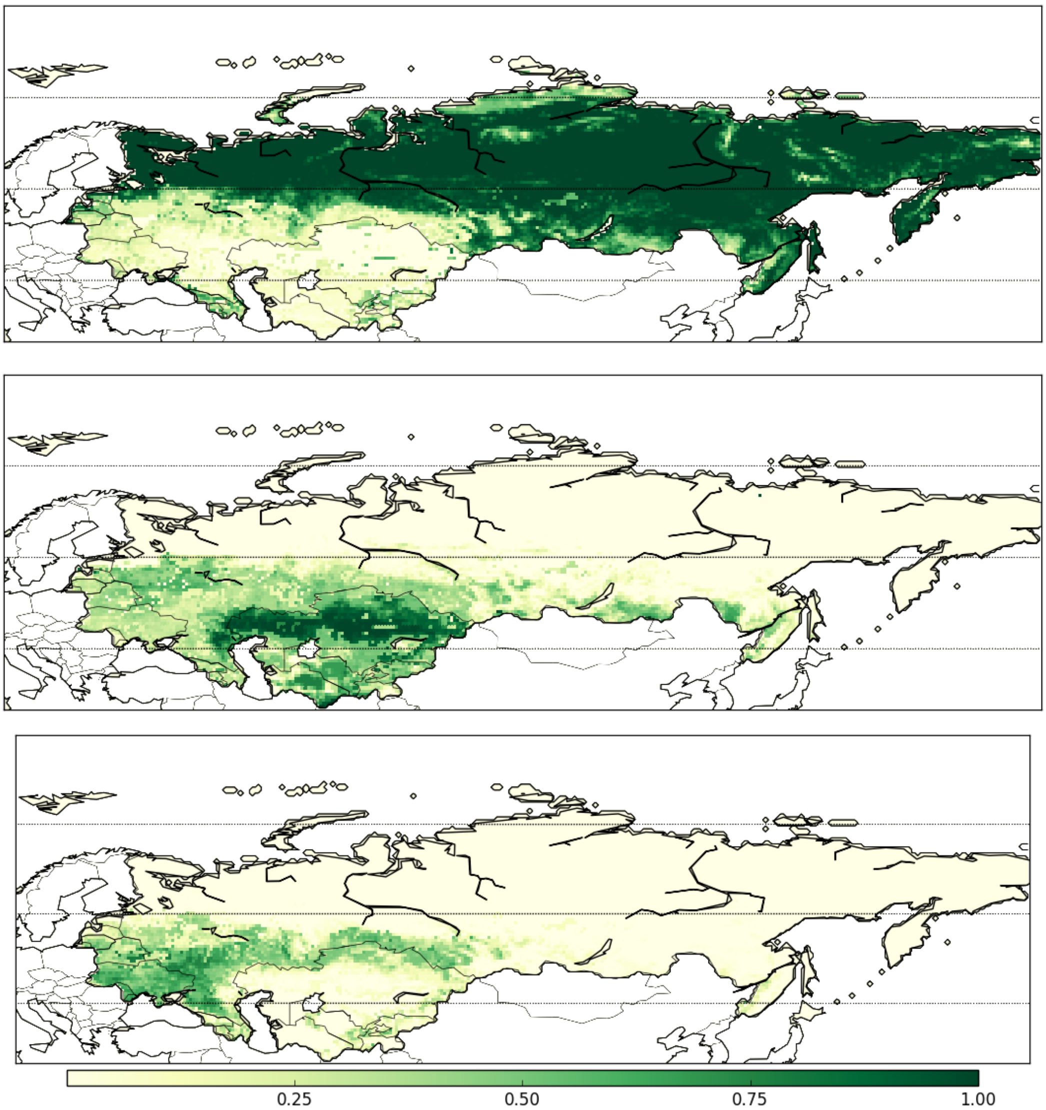

Figure S1 - Average spatial distribution of forest (top panel), grassland (central panel) and cropland (bottom) area fractions in FSU during the 20th century (1901-1999 average, consistent with the period used for simulations), converted from LU_{REF} to ORCHIDEE PFT classes.

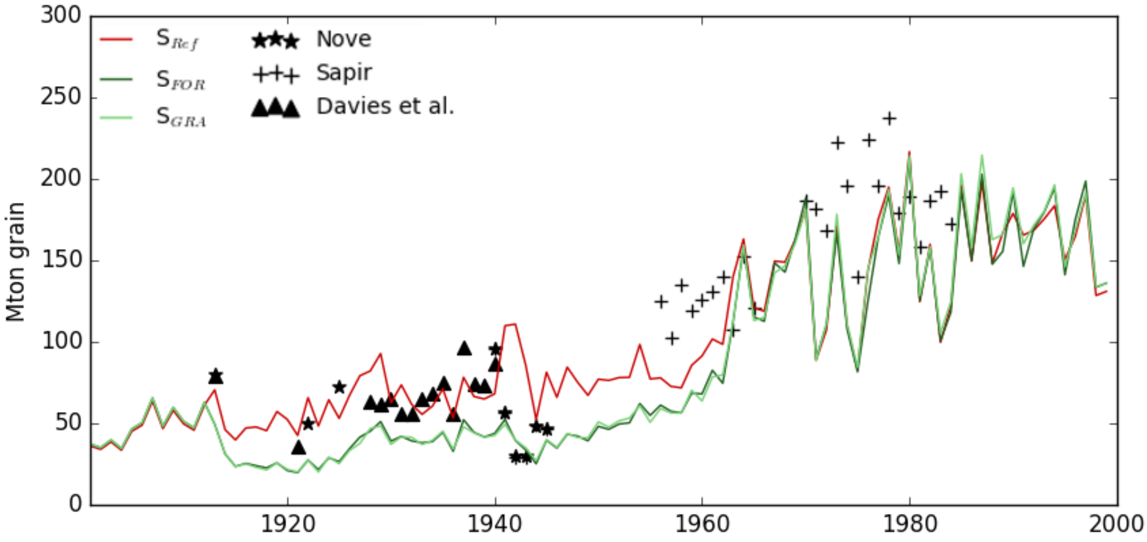

Figure S2 - Simulated harvest productivity (converted to grain production) in FSU from S_{REF} is in line with estimates of Soviet grain production until 1945 and captures the increase from the mid 1950s until 1980 reported in Nove (1982), Sapir (1989) and Davies (1994). The simulations using lower cropland extent (S_{FOR} and S_{GRA}) generally lead to underestimates of grain harvest, although in some years their estimates are closer to reported values (e.g. around 1930 and between 1940-1945).

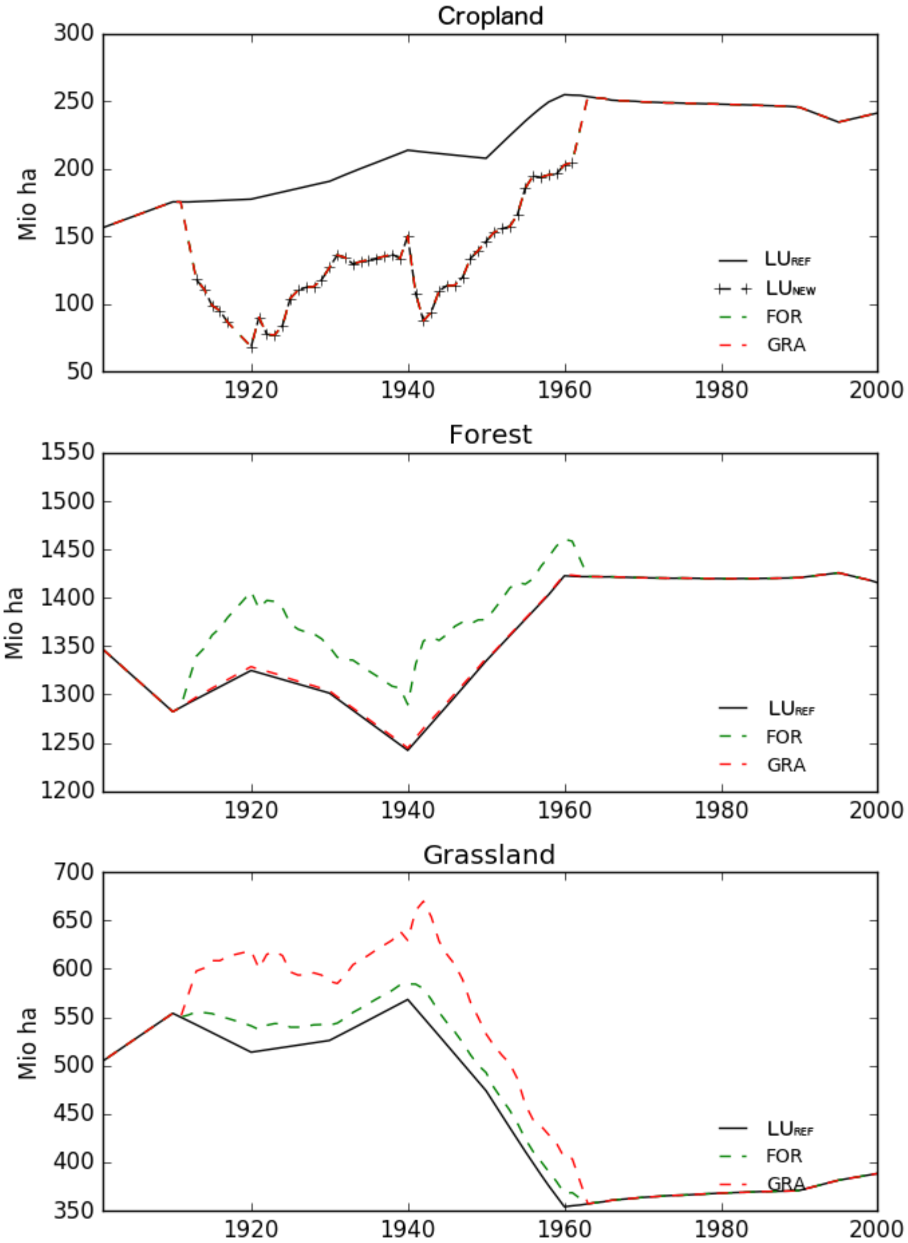

Figure S3 - Evolution of land-cover classes in FSU during 1901-2000, for LU_{REF} and LU_{NEW}. Cropland area in the FSU in the two datasets used here: LU_{REF} (plain line, black) and LU_{NEW} (1913-1961, markers). The corresponding updated values in the corrected land-cover maps used in the model simulations are shown in dashed lines, differing from LU_{REF} between 1912 and 1962 (LU_{NEW} period and interpolation of 1912 and 1962 values to produce a smoother transition). In panels b) and c), the total FSU forest and grassland in LU_{REF} and in the two updated datasets corresponding to each scenario: FOR (forest replacing cropland when possible, green) and GRA (grassland replacing cropland, red).

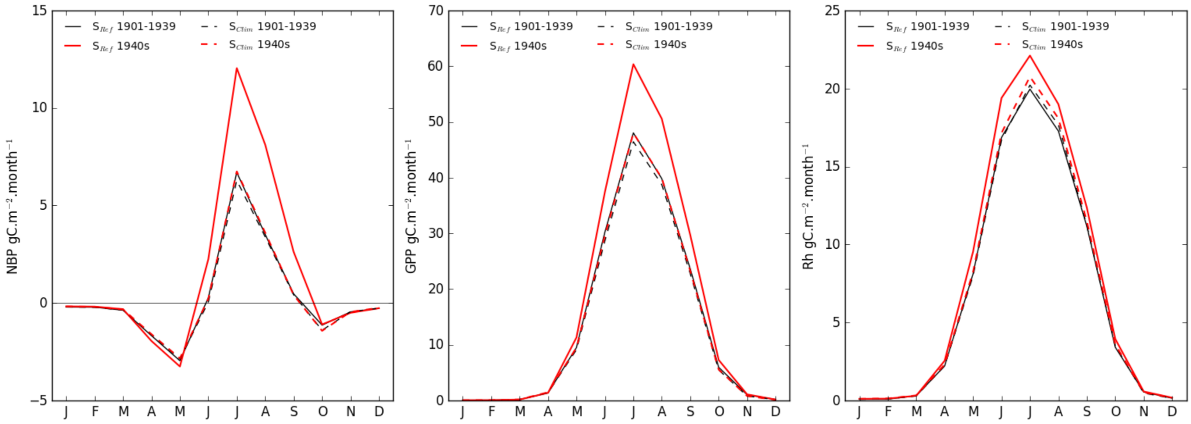

Figure S4 - Simulated seasonal cycle of NBP (left), GPP (centre) and heterotrophic respiration (right) in FSU during the 1940s in comparison with the previous four decades, for S_{Ref} and S_{Clim}.

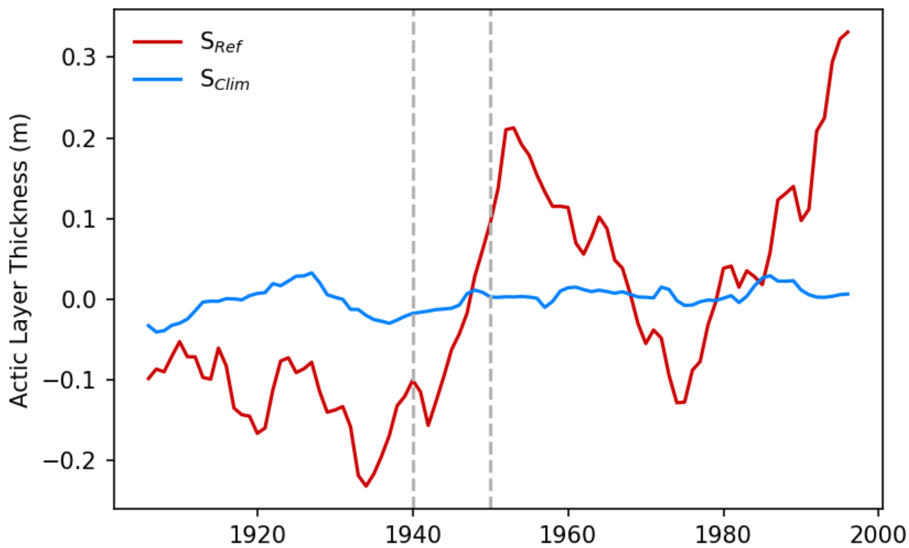

Figure S5 – Anomalies in the Active Layer Thickness (ALT) in the permafrost regions of the FSU territory simulated by S_{Ref} (CO2, climate and LUC) and S_{Clim} (CO2, LUC, and climate variability only). The model simulates a strong deepening of the ALT during the 1940s, promoting increasing soil-water availability that allows supporting enhanced vegetation growth over the growing season promoted by the spring warming (Figure **S4**). The long-term changes in simulated ALT in the last decades of the 20th century are consistent with results for sparse permafrost measurements over Russia presented in Lemke et al. (2007, their Figure 4.20), although higher than their average values.

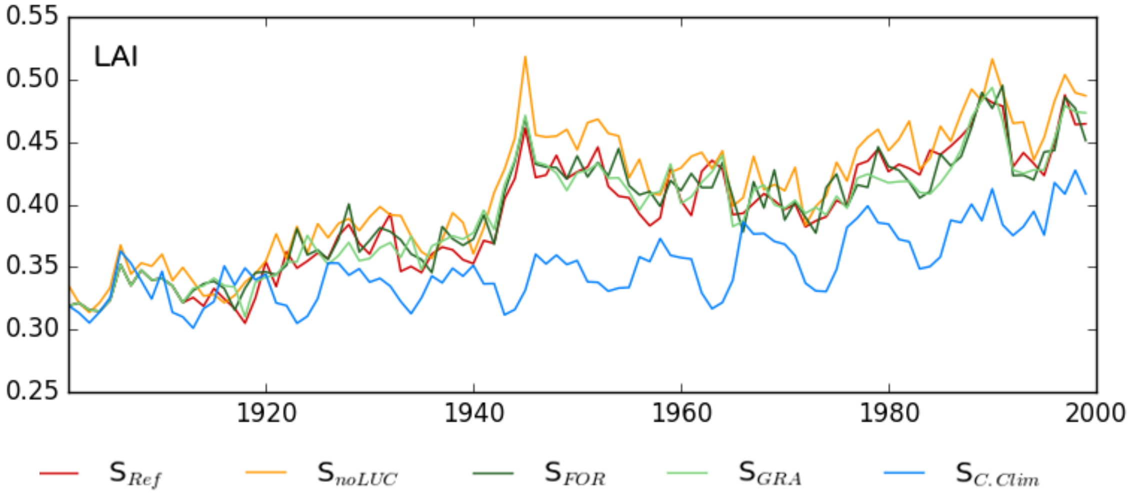

Figure S6 – Simulated Leaf-Area Index during the 20th century simulated by ORCHIDEE-MICT by the five factorial simulations. All simulations forced with observed climate indicate a peak of LAI increase slightly after 1940s, which indicates a temperature-related enhancement in vegetation growth. ORCHIDEE-MICT simulates vegetation productivity decrease due to soil freezing and limited access to deep water in permafrost soils. Therefore, the model estimates a stronger response of GPP and vegetation growth to winter/spring warming than other models that do not include such processes.

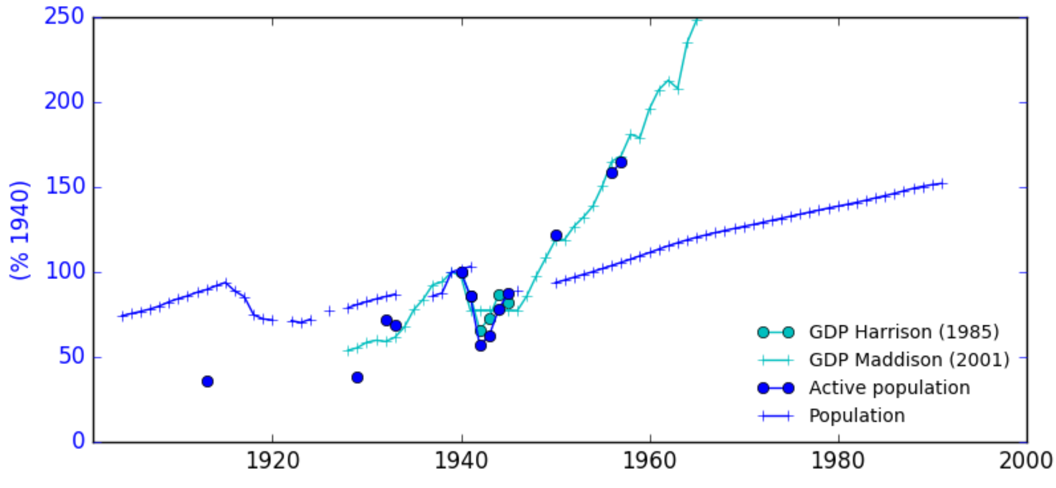

Figure S7 – Population and economic statistics. Values of GDP (light-blue) from two different sources are compared against the population and active population data from GOSKOMSTAT (blue). For comparability all values are provided in percentage (%) of the corresponding value in 1940 (100%). While GDP and total population are mostly independent at decadal time-scales, active population values closely track variations in GDP.

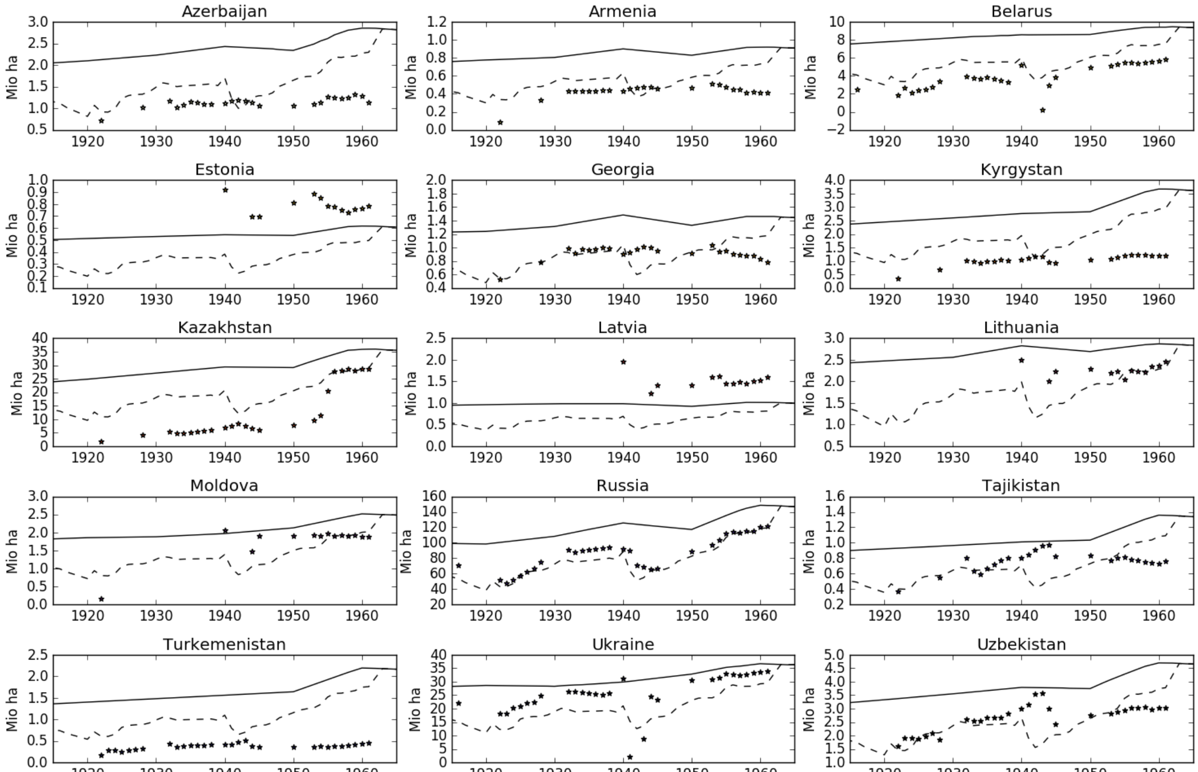

Figure S8 – Cropland area for former republics of FSU (now independent countries) in LU_{REF} (solid lines) and LU_{NEW} (dashed line). The values are compared to the country level official statistics (black markers). Please note the very different *yy* scales: the territory of Russia encompasses most of the cropland area and LU_{NEW} provides a very good match to country-level statistics.

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