Georgia’s potentials for sustainable intensification, increasing food security and rural incomes.

Authors:

Florian Gollnow[1,2,3,4], Owen Cortner[3,5], Shijuan Chen[1,5], Pontus Olofsson[6], Rachael Garrett[1,2,3]

Corresponding author: Florian Gollnow (florian.gollnow@sei.org)

Affiliations:

[1] Department of Earth and Environment, Boston University, Boston, MA, United States of America

[2] Department of Geography and Conservation Research Institute, University of Cambridge, Cambridge, United Kingdom

[3] Environmental Policy Lab, ETH Zürich, Zürich, Switzerland

[4] Stockholm Environment Institute, Stockholm, Sweden

[5] Yale School of the Environment, Yale University, New Haven, CT, United States of America

[6] NASA Marshall Space Flight Center, Huntsville, AL, United States of America

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Abstract:

Increasing global demand for agricultural commodities spurs conversions of natural ecosystems. Sustainable intensification in areas of high yield gaps has been proposed a pathway to achieve food security, support rural livelihoods, while also reducing the impact of commodity production by narrowing yield gaps on existing agricultural lands, while improving resource efficiency. Following the dissolution of the Union of Soviet Socialist Republics (USSR), Georgia experienced one of the highest losses of agricultural productivity among all former USSR countries and is now highly dependent on food imports. Closing yield gaps in Georgia through sustainable intensification has the potential to increase food self-sufficiency, support rural livelihoods, and strengthen food security and sovereignty. We estimated its potential for sustainable intensification in current agricultural areas to achieve self-sufficiency for wheat, maize, and barley. We found that crop yields can be doubled to tripled under high-input production systems, using high-yielding varieties, optimized inputs, fertilizers, and pest control. Yet, self-sufficiency in wheat can only be reached if at least 80% of the potentially attainable yields are achieved and if land is strategically allocated between crops. To achieve such increases, farmers need access to and training for using different crop varieties, fertilizers, and pest and disease control practices and products. Intensification increases the risks to ecosystem services' health and livelihoods, particularly raising equity concerns. Yet, intensifying very low input systems is often found to be more sustainable, with high yield increases compared to limited impacts on the environment. The high employment rate in the agricultural sector in Georgia particularly provides opportunities to reduce poverty and increase livelihoods through increasing incomes and food security.

1 Introduction

Increases in global demand for food commodities are expected to continue with ongoing trends or greater meat consumption in middle-income countries, increasing use of bioenergy, population increases, and little progress on reducing food waste. To meet national food security goals, countries can increase their reliance on international trade or increase domestic production. The first approach may be least costly but may increase the country's vulnerability to food crises caused by trade disruptions, climate change, political instability, war, and short-term market shocks (FAO 2015). Furthermore, reliance on international markets contributes to outsourcing of environmental harms to those exporting countries, not least of which includes habitat loss (Pendrill *et al* 2019, Curtis *et al* 2018) and embodied water loss (Chen *et al* 2021b, Han *et al* 2018).

To increase domestic production there are three options: closing yield gaps on existing agricultural areas, i.e., in areas where there are large differences between current and attainable production, relocating agriculture to areas of higher potential production, or expanding the overall agricultural area in the country. While the net environmental impacts of intensification and land sparing versus more expansive diversified farming remain a subject of intense debate, intensification carries two potential benefits of intense importance for global sustainability goals: first, supporting rural development and livelihoods by helping move farmers out of poverty traps (Beyer *et al* 2022), and second, contributing toward freeing up land to set aside for nature restoration (Meyfroidt *et al* 2018, García *et al* 2020).

The net sustainability benefits of intensification increase when done through sustainable intensification (e.g., optimizing fertilizer, pest, and disease control methods, using complementary crop rotations, crop-livestock integration, and improved soil management, and using high-yielding varieties) (Garnett *et al* 2013). In contrast, relocating agricultural production to areas with higher potential agricultural or expanding overall agricultural areas are likely to cause carbon emissions, habitat loss and fragmentation affecting biodiversity loss, and disrupt existing livelihoods (Meyfroidt *et al* 2022). These outcomes tend to be highly unjust as well, since most often it is the most vulnerable communities that suffer from their land being classified as optimal for conversion to other land uses and who are unable to have their voices heard in planning processes (Löfqvist *et al* 2022, Meyfroidt *et al* 2022). Intensification typically requires higher and more efficient use of inputs and machinery posing additional challenges such as pollution, pesticide resistance, degradation and others (Godfray and Garnett 2014, Tilman *et al* 2001, Cassman *et al* 2003, Cassman 1999). However, impacts are lower when intensifying from very low yield to more moderate yield levels, versus moving from moderate to high yields. For example, applying additional N fertilizer in low input agricultural systems has been found to hardly affect N_2O emissions, compared to adding the equivalent N in highly fertilized system (Shcherbak *et al* 2014).

Analyses of where yield gaps exist within countries and concrete estimates for how much closing these gaps through different intensification methods could contribute to reducing food insecurity are thus urgently needed. Coarse global analyses on the subject of yield gaps point to their high importance for global food security (Cassman and Grassini 2020). Yet high-resolution within-country analyses are rare. Such work has, for example, been published for China with a focus on self-sufficiency (Deng *et al* 2019), for Southeast Asia with a focus on rice import needs (Yuan *et al* 2022), and for Russia focusing on post-soviet wheat production (Schierhorn *et al* 2014, Schierhorn 2014). A better understanding of how to sustainably intensify yields in Eurasia is especially critical given that conflicts remain an ongoing and unpredictable pressure on food systems, often disrupting the food trade directly or the trade of food production inputs (Zhang *et al* 2023, Lin *et al* 2023, Mottaleb *et al* 2022, Puma *et al* 2015, Alexander *et al* 2022, Laber *et al* 2023).

The country of Georgia in the Caucasus region finds itself in a particularly challenging agricultural situation. Compared to other former USSR countries, Georgia experienced one of the highest declines in agricultural productivity with the resolution of the USSR. Agricultural productivity declined by around 40% from its mid-1980s levels until 1994 (Bezemer and Davis 2003, Lerman 2004) and did not experience substantial increases towards the 2020s (Geostat 2022, Bezemer and Davis 2003). Yet, land abandonment rates in Georgia were minimal compared to other former USSR countries (Lesiv *et al* 2018). Following the 2008 invasion by

Russia, Abkhazia and South Ossetian (Tskhinvali) remain de facto occupied territories, positioning Georgia in an ongoing conflict (Welton *et al* 2013, Janse 2021).

At the same time, Georgia is highly dependent on food commodity imports, particularly wheat from Russia, one of Georgia's main sources of dietary energy per person (36.2% daily dietary energy pp) (Geostat 2022, Jenderedjian and Bellows 2019, Mottaleb *et al* 2022). For example, in 2015, wheat self-sufficiency, i.e., the percent nationally produced from the total consumed production was only 17%, while 96% of the additional consumed wheat was imported from Russia (FAO 2020) (Table SI 1). Meat self-sufficiency was only 47%. However, self-sufficiency of other commodities, such as vegetables was quite high, at 87% (Kharaisvili 2017). Increasing self-sufficiency in wheat production in Georgia could be instrumental to regain power over food staples in Georgia, reducing its dependency from foreign, i.e., Russian, powers (Patel 2012).

In Georgia, the agricultural sector additionally plays a key role for poverty reduction and livelihoods. In 2012, around 25% of the rural population lived below the poverty threshold. Around forty percent of Georgia's population is employed in the agricultural sector, and agriculture is responsible for around forty-five percent of rural incomes (Gugushvili 2017, Kaczmarek-Khubnaia 2020). Sustainable agricultural intensification can help to reduce rural poverty by increasing incomes from higher production (World bank 2022, Kaczmarek-Khubnaia 2020, Ministry of Agriculture of Georgia 2017).

Here we aim to better understand Georgia's current self-sufficiency for major crop staples and how sustainable intensification could increase crop self-sufficiency, food security and food autonomy. We estimated the potential crop yield increases by comparing current yields to attainable yields as estimated by both the top-down framework of the Global Agroecological Zoning model (GAEZ v4) (FAO and IIASA 2021) and the bottom-up approach estimated by Gerber *et al* (2024). This allows us to compare our results between both modeling approaches, enhancing the interpretation and rigor of our estimates. With this we provide new insights into Georgia's food self-sufficiency and its potentials for sustainable intensification through yield increases.

The main research questions are:

- What is Georgia’s current self-sufficiency for major staple crops?
- What is the difference between current and attainable crop yields in Georgia and which land management strategies are most effective in closing the yield gaps?
- How would production gains on current agricultural land affect food security and autonomy?

1.1 Background

1.1.1 Study area

Georgia is located between the Greater and Lesser Caucasus mountains in the north and south and the Black Sea to its west. Landscapes and ecosystems change over short distances from the high mountains of the Greater Caucasus in the north-east, towards the foothills and large low-lands in the west, and from the Mediterranean climate by the Black Sea to the steppes in the east and southeast (Didebulidze and Plachter 2002, Buschmann 2020). Alongside its high ecosystem diversity, Georgia is rich in biodiversity and is identified as one of the worlds ‘biodiversity hotspots’ for its concentration of endemic species richness and, at the same time, loss of natural habitats (Myers *et al* 2000). Moreover, Georgia is considered one of the centers of origin for many domesticated plant and animal species (e.g., Mosulishvili *et al* 2019, Sikharulidze *et al* 2022).

In 2009 almost half of the land in the Caucasus region had been transformed by humans, with the plains, foothills, and subalpine belts the most impacted. For example, only 5-7% of the original floodplain ecosystems in the larger Caucasus remained intact in 2009 with most areas converted for agricultural production. In the Caucasus region as a whole, around 25% of natural ecosystems remain intact, and only 10-12%, including forests and high mountains, can be considered pristine (Zazanashvili and Mallon 2009). Rates of deforestation and land-use change since 1987 are small, with only 0.3% of Georgia found to be deforested (Olofsson *et al* 2010, Chen *et al* 2021a, Geostat 2022, Cortner *et al* 2022).

1.1.2 Institutional and land system changes

The dissolution of the USSR caused profound societal, institutional, economic, and land system changes (Stefes 2006, Buschmann 2020). Following independence in 1991, large collective and state-owned farmlands (Kohlkozes and Sovkhozes) were sequentially distributed across households to individually owned physical parcels of 0.25-5 ha. Each household received 0.75 ha on average (Kegel 2003, Kaczmarek-Khubnaia 2020, Buschmann 2020). On the one hand, this enabled individual families to pursue subsistence agriculture, thereby reducing their vulnerability to food shortages and price fluctuations during the transition and the emerging conflicts in Abkhazia and South Ossetia (Tskhinvali) (Kegel 2003, Jenderedjian and Bellows 2019). On the other hand, this caused a highly fragmented land system of small field sizes. Even though small field are not necessarily less productive than large field (Livny 2012), the reduced benefits of scale, the larger focus on subsistence agriculture, and lower trained landowners reduced previous productivity. In addition, deterioration of irrigation and drainage systems due to lack of maintenance after independence, high interest rates for agricultural investments (Welton *et al* 2013), unfavorable taxation practices (Natishvili and Gubelatze 2018), and a lack of property registration, which obstructs land investments and sales (Welton *et al* 2013, Kochlamazashvili *et al* 2018), have limited agricultural productivity.

During the early 2000s, Georgia realized impressive economic growth, fueled by neoliberal reforms and anti-corruption measures implemented between 2004 and 2012. Georgia's Gross National Income (GNI) per capita increased from US$1,120 in 2004 to US$4,490 in 2014 (in 2017 USD) (Gugushvili 2017). However, rural poverty levels remained largely unaffected (Gugushvili 2017). Since 2011, the Georgian government has significantly increased the budget of the agricultural ministry, with the aim of increasing food safety and security (Ministry of Agriculture 2015). A key strategy was to incentivize and support the development of agricultural cooperatives to leverage scale effects and thereby overcome limitations of small, fragmented farms (Welton *et al* 2013, Gelashvili 2020, Gugushvili 2017). The Georgian government and international donors provided support including training, grants and credits (Millns 2013). Efforts to increase land registration were expanded to ensure definite land titles for farmers and enable a functioning land market (Kochlamazashvili 2019). In addition, since

2017 large investments have been targeted to recover and expand Georgia's irrigation and drainage systems to increase yields and reduce the risk of seasonal precipitation shortages (Ministry of Agriculture of Georgia 2017, Natishvili and Gubelatze 2018). In total Georgia aims to irrigate 200.000 ha by 2025, an increase by a factor of 2.3 from 2015 (88,000 ha) (Natishvili and Gubelatze 2018), but still less than half of the irrigated area in 1989 (469,000 ha) (Branscheid 1998).

2 Methods & data

Self-sufficiency in agricultural commodity production is a key indicator for understanding countries' availability of and risks associated with food supply among the four main pillars of food security, i.e., availability, access, utilization, and stability (FAO 2015, Clapp 2016). First, we calculated Georgia's *self-sufficiency ratio* (SSR) for wheat, maize, and barley, three of the major annual staple crops produced in Georgia's agricultural statistics (Geostat 2022) and import and export statistics obtained from FAO (FAO 2020) for the years 2006 to 2019. The SSR is defined as the percentage of national production compared to the overall national consumption (Formula 1 below) (FAO 2013, Clapp 2017). Higher self-sufficiency ratios decrease a country's vulnerability to food shortages, caused by, e.g., trade disruptions, war and conflicts, and price volatility. Countries achieving 80-120% self-sufficiency are considered to produce roughly the same amount of food that they consume (Clapp 2016). Self-sufficiencies above 100% for specific commodities indicates production exceeding the national demand, which is common for exported production.

$$SSR = \frac{Production}{(Production + Imports - Exports)} \times 100 \qquad [1]$$

To analyze Georgia's potential for achieving self-sufficiency across the three crops without additional land conversion we applied an 80% and 100% SSR threshold, as an SSR above 80% is considered to be least vulnerable to food shortages (Clapp 2016).We then derived current and potentially attainable yields for Georgia's main annual staple crops, wheat, maize and barley. We acquired current yields from the Georgian agricultural statistics (Geostat 2022). We used two distinct datasets to derive potentially attainable yields, first the Global Agro-Ecological Zones (GAEZ) database provided by the FAO and IIASA (FAO and IIASA 2021) and attainable yield estimates by Gerber *et al* (2024). Attainable yields can be defined as the yield a skillful farmer reaches under the local biophysical conditions when accounting for economic and risk factors of production (Foulkes *et al* 2022). The datasets were generated using two very different approaches. The GAEZ models potentially attainable yields using a top-down approach based on the spatial explicit thermal, moisture, agro-climatic, soil and terrain conditions derived at the specific location of interest, under selected land management options(FAO and IIASA 2021). Gerber *et al* (2024) estimated attainable yields using a bottom-up approach, defined as the highest 95% quantile of observed yields derived using annual yield and harvest data compiled following the methods in Ray *et al* (2019). In the case of Georgia, yields represent the national average of attainable yields for the selected crops for each year between 1975 to 2010 (Gerber *et al* 2024). Data on current yields of wheat, maize, and barley were derived from Geostat (2022) and available for at regional level for all of Georgia, excluding the occupied territories of Abkhazia and South Ossetia (Tskhinvali) (Figure 1, Figure SI 2-8). Yield data were provided as fresh harvest tons per hectare and converted to dry weight using the conversion factors in Fischer *et al* (2021).

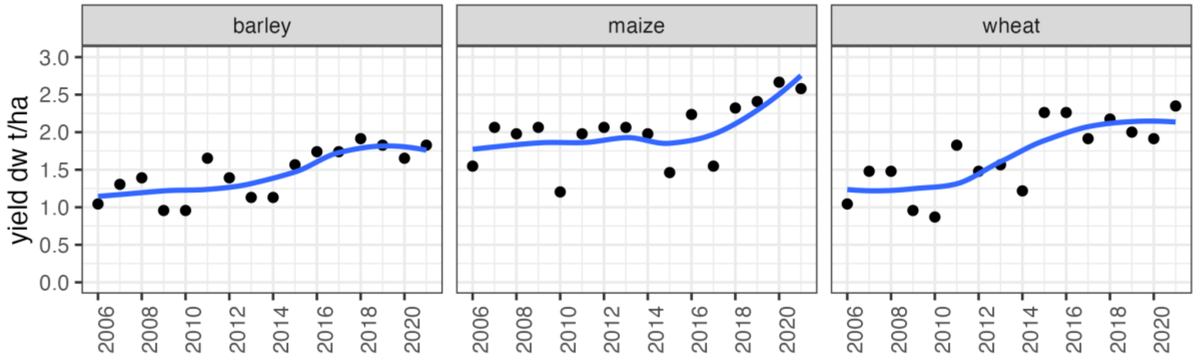

Figure 1: Average yield in Georgia for grain crops. Note all crops experienced a yield increase since the 2000s.

The GAEZ v4 model provides a spatial explicit gridded, datasets at 5-arc minute (9.25km at Equator) resolution, representing the estimated agro-ecological attainable dry-weight in tons per hectare under current climate conditions (30-year average between 1990 and 2020) (FAO and IIASA 2021). With this, GAEZ estimates of attainable yields incorporates Georgia's high variability in landscapes and ecosystems. This is different to estimates by Gerber *et al* (2024), providing an average attainable yield estimates at national level (gridded dataset at 5-arc minute). By using two different estimation approaches, i.e., top-down (GAEZ) and bottom-up (Gerber *et al* 2024), we are able to compare and understand variability and uncertainty of the attainable yield estimates based on the different modelling approaches, and thereby enhancing the interpretation and rigor of our analysis.

The GAEZ dataset provides 4 different crop management types derived from combining low and high-input input (nutrient and pest) land management and rainfed and irrigated water management:

- Low-input agriculture is described as traditionally managed, largely subsistence-based farming systems, assuming the use of traditional cultivars, labor intensive techniques, with no application of plant nutrients, and of chemicals for pest and disease control and minimum conservation measures. Fallows are required to maintain soil fertility (Fischer *et al* 2021).
- High input farming systems are assumed to be mostly market oriented. Production is based on improved, high-yielding varieties, and is fully mechanized where possible. High-input farming attempts to optimally apply nutrients, and controls for pests, diseases and weeds (Fischer *et al* 2021).
- Rainfed systems, can be low or high input, but are limited by water availability during the growing season.
- Irrigated systems assume that irrigation is scheduled such that no yield-reducing crop water deficit occurs during the crop growth cycle (Fischer *et al* 2021).

Across these four options, for the purposes of this study we characterize high input, rainfed systems as the sustainable intensification option on current croplands (no conversion of natural vegetation), assuming good agricultural practices of input application, whilst also providing potential for increasing yields and benefits to food security.

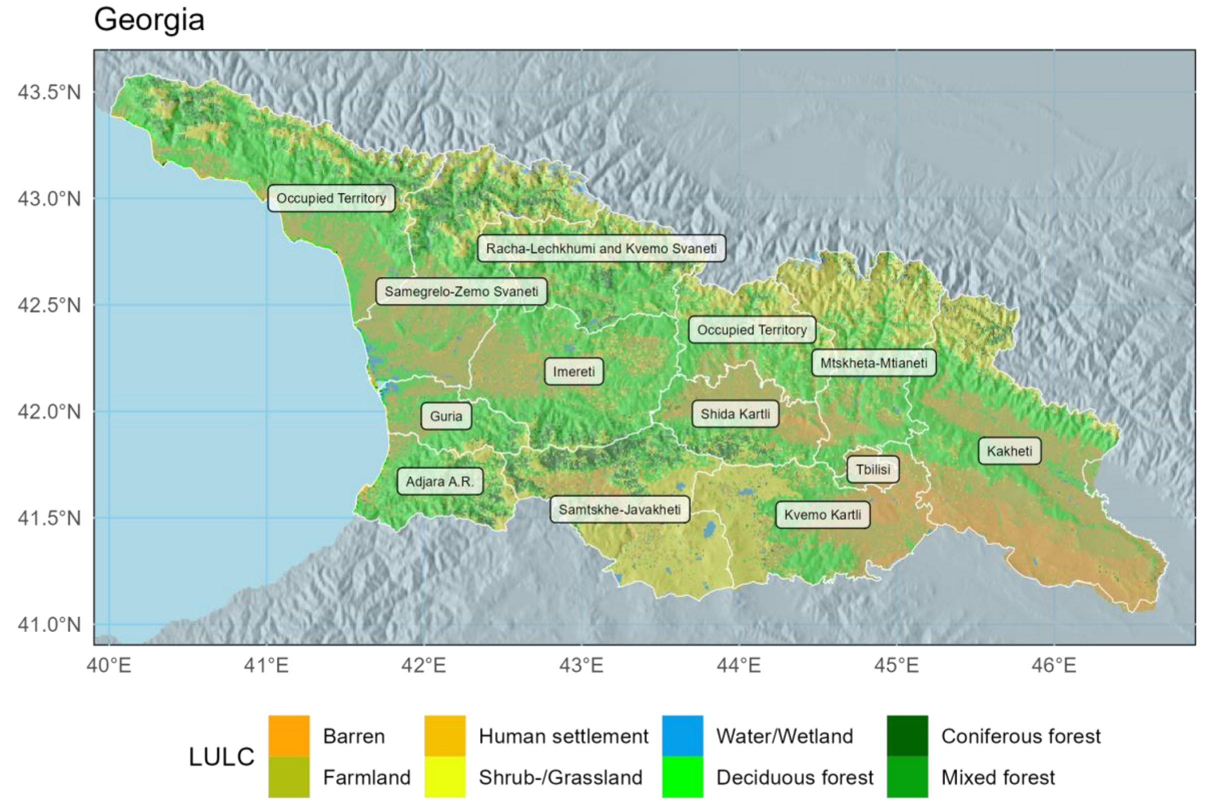

Figure 2: Land use and land cover (LULUC) in 2019 in Georgia based on Chen et al. (Chen et al *2021a*). *Occupied territories are, in the north-west, Abkhazia, and in the center-north, South Ossetia (Tskhinvali).*

We extracted the attainable yield from the GAEZ data at the location of annual agriculture (Chen *et al* 2021a) at 90 m resolution (Figure 2, SI $1). Following, we summarized the GAEZ attainable yields as the mean potentially attainable yields derived at the location of annual agriculture (Chen *et al* 2021a) weighted by the respective crop production per region derived from Geostat (2022). With Gerber *et al* (2024) providing national constant fresh harvest yields we extracted yields for 2010 directly from the dataset and converted them to dry weight using the conversion factors in Fischer *et al* (2021). We calculated yield gaps as the difference between the current and attainable yields.

Attainable yields usually describe the yields achievable given economic, biophysical and climatic risks. With that the attainable yield is often by around 20% lower than the potential yield. With yields approaching the potential yield threshold, it becomes increasingly difficult to sustain yield increases because further increases require the elimination of small imperfection in crop management which are not economically viable to eliminate (Cassman *et al* 2003, Foulkes *et al* 2022, Schierhorn 2014, Deng *et al* 2019, Lobell *et al* 2009). Given this increase in difficulty to close yield gaps with increasing yields we calculated and reported two yield gap closure scenarios, defined by 80% and 100% exploitable attainable yields *to close the yield gaps.* Similarly, not all areas are suitable for irrigation, and irrigation systems are often costly, making them more appropriate for high value agricultural commodities such as fruits and nuts.

Next, we assessed the *self-sufficiency ratio under the different attainable yields*. All crop production increases were assumed to be based on yield increases alone. The area for each crop was fixed at its 2019 area extent based on Georgian agricultural statistics (Geostat 2022).

Finally, we extended the scenarios to maximize wheat self-sufficiency while keeping maize and barley production at 100% and 80% self-sufficiency. To do this we first calculated how much area could be spared from producing maize and barley under 80% and 100% attainable yield, to achieve 80% and 100% of self-sufficiency for each region. Second, we evaluated how much additional wheat could be produced on these areas under 80% and 100% attainable yields and compared this to Georgia's wheat self-sufficiency demands. This analysis allowed us to understand if Georgia would be able to achieve wheat sufficiency, without trade-offs in the self-sufficiency of other crops, - i.e. if Georgia would be able to reduce its reliance on imports from Russia and increase food security and sovereignty.

3 Results

3.1 Food self-sufficiency for annual staple commodities in 2019

Evaluating Georgia's self-sufficiency for three annual crops (wheat, maize, barley), we found a particular dependence on wheat imports, with 84% of Georgia's wheat consumption relying on imports in 2019 (16% self-sufficiency) (Figure 3). Maize self-sufficiency was at around 70% in 2019, declining from around 100% in 2012 (Figure 3), partly due to reduced production (Figure SI 1 & Figure SI 5-8), while yields for all crops increased during the same time (Figure SI 2-4).

Barley self-sufficiency remained high during all years of observation, with Georgia a net exporter of barley in 2019 (Figure 3).

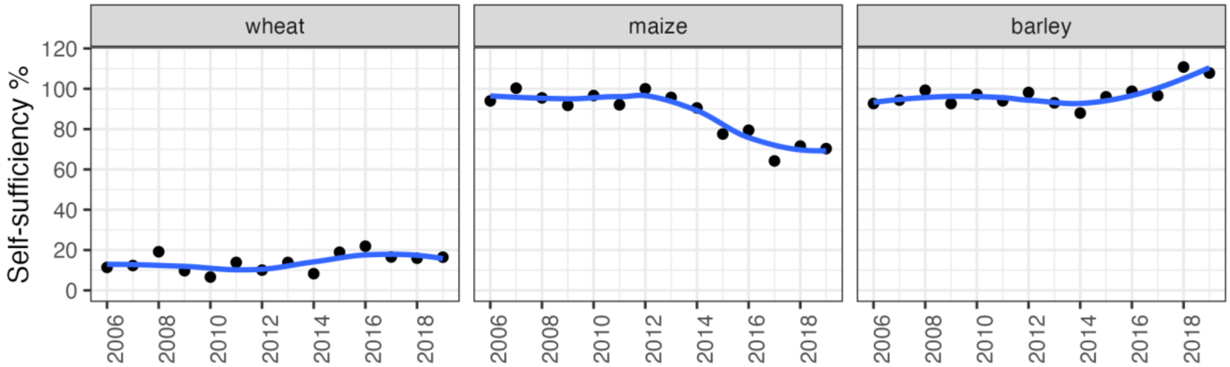

Figure 3: Self-sufficiency ratios (see formular 1, above) for wheat, maize, and barley in Georgia.

3.2 Actual vs. attainable yields

Actual yields closely match GAEZs estimates of low-input rainfed agriculture. Compared to the GAEZ low-input agriculture yield estimates, currently attained yields as a percentage of the modeled attainable yields were 75% for wheat, 104% for maize, and 71% for barley (Figure 4). Compared to Gerber *et al* (2024) attainable yields, current yields where around 36% for wheat, 25% for maize, and 31% for barley (Figure 4).

The GAEZ model suggest that high-yielding varieties, optimized fertilizer application, pest, and disease control (high input rainfed attainable yields) could increase yields to a maximum of 7.5t/ha (from 2.1 t/ha) for wheat, 8.1 t/ha (from 2.6 t/ha) for maize and 7.3 t/ha (from 1.8 t/ha) for barley. Using the full potential of attainable yields according to Gerber *et al* (2024), yield estimates reached to 5.7t/ha (from 2.1 t/ha) for wheat, 10.3 t/ha (from 2.6 t/ha) for maize and 5.9 t/ha (from 1.8 t/ha) (Figure 4).

At 80% of yield gap closure, GAEZs high input rainfed agriculture yields would be 6.0 t/ha for wheat; 6.4 t/ha for maize; and 5.8 t/ha for barley, respectively (Figure 4). Under 80% yield gap closure following Gerber *et al* (2024) attainable yields, yields would reach 4.5 t/ha for wheat; 8.2 t/ha for maize; and 4.7 t/ha for barley (Figure 4). Irrigation systems would further increase yields, which suggests productivity growth is water-limited, and that increases in irrigated areas would reduce the risk of yield losses during droughts and longer-term climate-driven changes in precipitation.

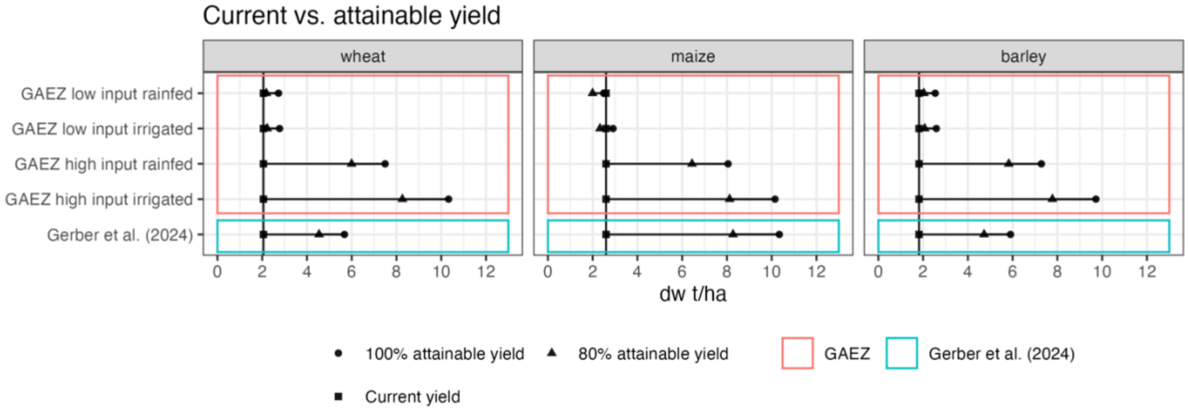

Figure 4: Current vs. attainable yields for wheat, maize, and barley. The vertical line represents the current yield derived from Geostat (2022). .

3.3 Production gains on current agricultural lands & crop self sufficiency

Adapting land management to high-input agriculture (following the GAEZ model), or exploiting the potential attainable yield following Gerber *et al* (2024) without changing the production areas for each crop, as recorded in GEOSTAT for 2019 (Geostat 2022), would reduce, but would not close the self-sufficiency gap for wheat, and would lead to above self-sufficiency production of maize and barley (GAEZ, rainfed and irrigated) and Gerber *et al* (2024) estimations (Figure 5). From currently 16% wheat self-sufficiency yield increases to 100% of the GAEZ attainable yields on current wheat production areas would reduce the self-sufficiency gap to 22% for low input rainfed, 61% for high input rainfed and 84% for high input, irrigated crop production. If 100% of the attainable yields of Gerber *et al* (2024) were achieved on current wheat production areas the wheat self-sufficiency gap could be reduced to 45% (Figure 5).

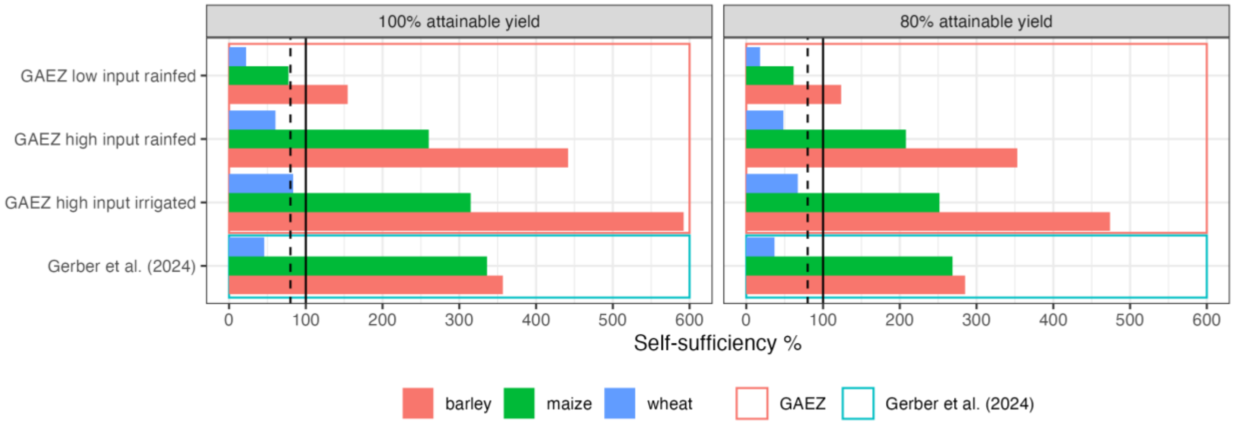

Figure 5: Self-sufficiency for wheat, maize, barley under the two different yield gap closure (left to right) and GAEZ crop management and Gerber et al (2024) attainable yield estimate on current crop production areas. Dashed lines indicate 80% self-sufficiency and solid line marks 100% self-sufficiency. Note that self-sufficiency of wheat is not reached, while maize and barley achieve self-sufficiency under GAEZ's high input assumptions and following Gerber et al.'s attainable yield estimates.

Only GAEZ's *high input irrigated* crop management under 100% of yield gap closure would reach the 80% self-sufficiency in wheat production (27.8 ktons, 2.2 kha) (Figure 5), which is an unlikely scenario, as irrigation for wheat across all production regions Georgia is extremely costly to implement and maintain.

However, the ability of intensification to increase maize and barley production above self-sufficiency enables a strategic potential to reduce the areas allocated to maize and barley in favor of wheat production without compromising self-sufficiency of those crops. We fixed maize and wheat at 80% and 100% self-sufficiency to understand how much additional wheat could be produces on the areas spared, and if those areas, when used for wheat production could close Georgia's self-sufficiency gap in wheat. Our calculation indicates that, if maize and wheat production were fixed at 80% and 100% self-sufficiency the additional area available for wheat production would meet and exceed Georgia's wheat self-sufficiency demand under 80% and 100% yield gap closure for GAEZ's high-input rainfed and irrigated crop production and under Gerber et al.'s attainable yield estimates (Figure 6).

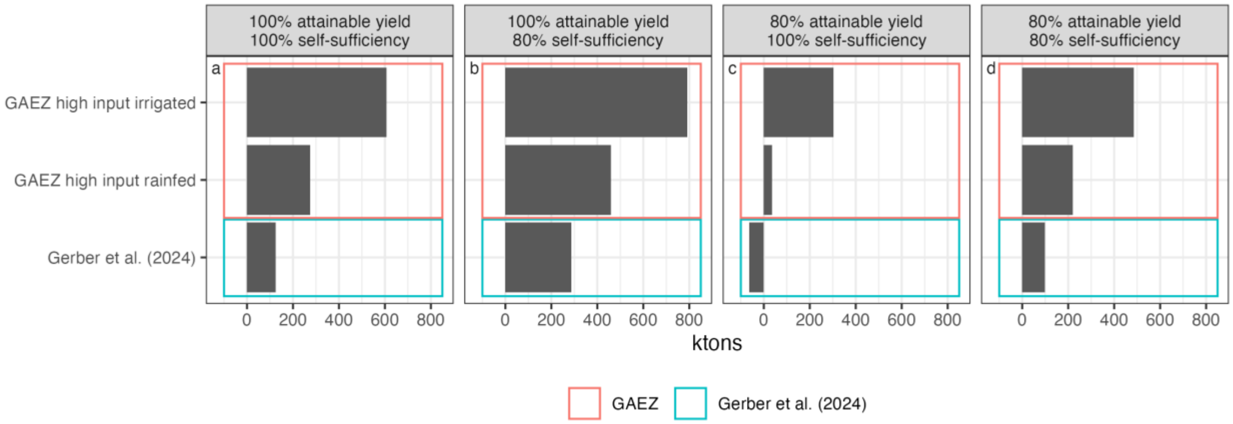

Figure 6: Wheat production differences at 100% (panel a and b 1 and 2) and 80% (panel c and d) attainable yields from 100% (panel a and c) and 80% (panel b and d) self-sufficiency including wheat production on spared land from maize and barley under the same 100%, 80% attainable yield assumptions. Zero indicates no difference between the self-sufficiency level and production, while positive values indicate above and negative below self-sufficiency wheat production (for area estimates see Figure SI 8). Notably, if 100% attainable yields are achieved across wheat, maize and barley, we find that wheat self-sufficiency can be achieved and surpassed under all 3 attainable yield estimates (while holding maize and barley production fixed at 100% self-sufficiency) (panel a). If 80% self-sufficiency across all crops would be aimed for, the attainable yield estimates suggest a larger surplus production (panel b) compared to the 100% self-sufficiency goal (panel a). Under the assumption that 80% attainable yields were achieved, we find that 100% wheat self-sufficiency would be achieved for the GAEZ estimates, but not for Gerber et al's (2024) estimate (panel c). However, aiming for 80% self-sufficiency, all three yield estimates suggest reaching the 80% self-sufficiency goal (panel d).

4 Discussion

Georgia has large potentials for sustainable intensification, increasing its self-sufficiency and food security, and in turn, attaining greater independence from foreign food imports and power dependencies. Current agricultural yields in low intensity rainfed production systems in Georgia could potentially triple if the attainable yield potential were exploited. This could be accomplished with the planting of high-yielding varieties, increased fertilizer application, , improved pest and disease control, and increased mechanization. GAEZ data suggest that irrigation could additionally boost yields and reduce risks of harvest losses in case of lack of precipitation during the growing season. Considering the ongoing Russian aggression, and de facto occupation of Abkhazia and South Ossetia (Tskhinvali), achieving independence from Russian wheat imports for food security might be critical for increasing national sovereignty. Yet, while sustainable intensification can contribute to food self-sufficiency, it would also increase Georgia's reliance on fertilizer imports. Diversifying import sources beyond Russia, Georgia’s current main wheat and fertilizer supplier (Chatham House 2021), would be critical to avoid transitioning from one dependency to another.

However, achieving 80% self-sufficiency for wheat, maize, and barley on currently used agricultural lands is challenging. Yields would need to increase to 80% or 100% of the attainable yields and wheat crops would need to expand over areas currently used by maize and barley to achieve an 80-100% self-sufficiency in wheat, maize and barley production on current crop areas (Figure 7). Incentivizing such a change from maize and barley to wheat production requires strategic and efficient agricultural policies providing credits and incentives and ensuring the availability of seeds and inputs for intensification and wheat production. However, we also note that the datasets used for this analysis come with uncertainties. GAEZ data for example has often been criticized for its approach, which was found to often underestimate potentially attainable yields (Edreira *et al* 2021). At the same time, the lack of subnational spatial variation in Gerber *et al's* (2024) attainable yield estimates does not well represent the heterogeneity of landscapes in Georgia (e.g., see the differences in observed yields by region in Figure SI 3-5). However, using both datasets in concert, which were derived using different methodologies yet achieved very similar results, we believe that our results and conclusion are robust to the uncertainties to each dataset.

In addition to increasing food security and self-sufficiency, increasing yields has the potential to increase human well-being, through increases in incomes, food security, and poverty reduction (Rasmussen *et al* 2018). Georgia, coming from a largely agrarian society with a low input agriculture system matches similar characteristics which have been described to often result in win-win situations, where intensification resulted in increases in well-being and benefits for ecosystem services, as described by (Rasmussen *et al* 2018). Hence, one of the main challenge to increase yields, food security and reduce poverty lies in providing access to inputs and seeds to all landholders to avoid benefitting the most powerful, while excluding the least powerful (Rasmussen *et al* 2018). This may be particularly challenging in Georgia due to the often-unclear land tenure and highly fragmented land system in Georgia.

Sustainable intensification of agricultural production may also come with environmental costs: if inputs are not optimally applied damage to natural ecosystems can occur (e.g., harm to pollinators, nutrient runoff into waterways), and crop diversity and resilience could decline. Meanwhile higher profitability may increase demand for land, spurring an expansion of agriculture into natural ecosystems (Tilman *et al* 2001). To minimize environmental consequences, it is imperative that the application of inputs and crop management is optimized and that farmers have access to training and support of good agricultural practices. Shcherbak et al (2014) suggest that following good practice for applying additional N fertilizer in low input agricultural systems, such as the current system in Georgia, has a minimal effect on N_2O emissions (Shcherbak *et al* 2014).

Historically, Georgia is home to one of the largest genetic wheat diversities globally. Yet in the 20th century, most old and endemic wheat varieties were replaced by modern breeders' varieties in (Bedoshvili 2008), and only five endemic wheat varieties are actively sown (Gelashvili and Mamardashvili 2017). However, the most frequently grown varieties are low-yielding and poorly adapted to the regions (Sikharulidze *et al* 2022). Field experiments show that high quality regionally-adapted varieties of wheat can double to triple currently achieved wheat yields - supporting the results of the analysis in this paper - while also being more resilient against diseases and providing high quality grains (Sikharulidze *et al* 2022).

Another risk of intensification is the risk of rebound effects, where higher yields and profits may incentivize agricultural expansion into new areas instead of sparing land from production (Meyfroidt *et al* 2022). Hence, support for intensification should be accompanied by sensible environmental regulations limiting the conversion of natural ecosystems to warrant sustainable agricultural growth that combines conservation and development.

Land fragmentation and lack of registration may be among the largest challenges for sustainable intensification. Lack of land titles hamper a functioning land market and may reduce farmers incentives to invest in improved production systems (Neudert *et al* 2019, Lawry *et al* 2017, Kochlamazashvili 2019). While some land concentration may be desirable to take advantage of production at larger scale (Kochlamazashvili 2019), high land concentration and large-scale land acquisitions may increase inequalities and marginalize less powerful actors and smallholders (Oberlack *et al* 2016, Meyfroidt 2017, Chiarella *et al* 2022). Medium-scale commercial farms that foster labor productivity, provide income, and integrate into retail value chains are often seen to play a crucial role in balancing the trade-offs between employment, food security, and poverty reduction. Georgia's strategy of incentivizing and supporting agricultural production or service cooperatives can be a way to achieve such benefits without sacrificing land ownership and/or access, reducing the risk of increasing inequality and exclusion (Chokheli and Javakhishvili 2018, Lerman and Sedik 2014, Lerman 2004). The most relevant benefits of such agricultural cooperatives are cost reduction, market access, mutual assistance between members, and access to financial resources. Starting in 2012, the Georgian government expanded its support of agricultural development to increase the quality of rural livelihoods, reduce poverty, drive rural development, and increase food security. They particularly incentivized the formation of cooperatives with a change in taxation and new grant systems in 2013, leading to around 1300 registered cooperatives in Georgia in 2018. Yet, many of those are not active and lack support in formal structuring operational knowledge, and information on the potential benefits (Chokheli and Javakhishvili 2018, Kochlamazashvili *et al* 2017).

Given the high potential for intensification in grain production, we may also expect additional potential for yield increases across other agricultural commodities. This could further increase Georgia's food self-sufficiency, incomes, and provide opportunities for land sparing beyond the current analysis including wheat, maize and barley.

5 Conclusion

Decreasing Georgia's dependency on major food staple imports is important for Georgia's food security and national sovereignty, given past and current conflicts with Russia and the major wheat trade disruptions caused by the Russian invasion of Ukraine in 2022. At the same time, with around 40% of the Georgian population being employed in the Agricultural sector, intensification of production has the potential to reduce poverty and support livelihoods in Georgia, through higher incomes from increased yields.

In this analysis we showed that Georgia's agroclimatic conditions allow for increasing self-sufficiency to almost 80% in wheat, maize, and barley production without additional conversion of natural ecosystems through sustainable intensification. Yet, to reach self-sufficiency in wheat production, wheat planting will need to be expanded to areas that can be spared from maize and barley or other annual crops following intensification to reduce the current yield gaps. Intensifying other agricultural crops may additionally increase production and incomes, or spare land, which could be used for further increasing food self-sufficiency. Policies incentivizing and supporting such a transition need to ensure access by all landholders, to be effective in supporting livelihoods and reducing poverty, instead of benefiting only the most powerful actors. Initiatives to support and form cooperatives have the potential to support inclusive and equitable rural development, since current gaps in access to training, agricultural credit, and financing hamper agricultural sector development. Policies increasing the support (e.g., information, knowledge, technology, credit) and incentives to establish agricultural cooperatives, expanding land registration, incentivizing wheat production, and providing access to regionally adapted and high-yielding crop varieties, fertilizer, and pest control alongside agricultural training can support food security and sovereignty and reduce rural poverty.

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