# Multi-model framework to assess food supply and demand gaps: A Pakistan case-study

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# Introduction

As stated by Sustainable Development Goal (SDG) 2, the aim of the international community is to achieve "zero hunger" by 2030. Currently 783 million people are still facing hunger and 2.4 million people do not have access to nutritious safe and sufficient food (FAO, IFAD, UNICEF, 2023). Food insecurity is therefore still a major global problem, which deserves urgent attention. “Food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life” (FAO, 1996).

Following this definition, both the supply (availability) and demand (accessibility) of food are major determinants of food security. Both food demand and supply are affected by a wide range of interconnected global (e.g. climate change, international conflicts and trade barriers), national (population and GDP growth, and technical change) and local (climate, soil and local food preferences) drivers. To assess whether progress towards SDG2 is on track and to formulate target policies to support food security, policy makers require insights on how food supply and demand will change in the future and which measures can be taken to ensure that sufficient nutritious and affordable food is available and accessible.

To grasp with the high-level of complexity and uncertainty, simulation models combined with scenario analysis are the standard approach to assess future food security. For example, (Van Ittersum et al., 2016) use crop simulation models to investigate by how much cereal yield needs to be increased in Africa to ensure sufficient food is produced for a growing population by 2050 without increasing import dependency. A similar approach is used by (Yuan et al., 2024) to assess the self-sufficiency in rice production in Africa. Other model studies focused more on the accessibility dimension of food security. (Hasegawa et al., 2015) uses an integrated assessment model to present different long-run global scenarios for the risk of hunger. Similarly, (van Meijl et al., 2020) presents a variety of food security indicators using two different simulation models using an alternative scenario framework.

Unfortunately, existing global simulation studies of food security are highly aggregated and are therefore often not able to produce projections of food demand and supply at subnational scales, nor do they capture the household and spatial drivers of food demand and supply. Precisely this level of detail is required to obtain insights on the local risks of food insecurity, such as the impact of a drought or flood on local food supply, and guide local policies to combat hunger, such as social protection programs and agricultural support (e.g. fertilizer and seed subsidies). To be effective, these interventions need to target local needs and take into account local conditions, which may vary considerably even within countries due to spatial differences in population density, urbanization and climate.

In this paper, we present a multi-model framework that makes it possible to assess food demand and supply at the subnational level under different socio-economic scenarios. We used a global economic simulation model with national detail to assess the global and macro-economic drivers of food demand at country level. The macro-level food demand and supply projections were subsequently ‘downscaled’ to the subnational level by (a) using a spatial microsimulation model to produce subnational food demand projections and (b) applying a hydrological and crop-simulation model combined with a land-use model to generate gridded food supply projections. The food demand and supply maps can be combined to determine the gap between (future) food demand and supply at the district level. Although subnational food self-sufficiency is not an objective perse because international and intra-country trade are key for food security, the identification of districts with large food supply-demand gaps will provide information on which areas are vulnerable to shocks, e.g. the share of people affected by local extreme climate events. Similarly, the modelling approach could be used to analyze how a change in dietary patterns, such as the adoption of the EAT-Lancet diet, will affect subnational food demand and supply balances.

We used Pakistan as case-study to illustrate our modelling approach. The country is ranked 102nd out of the 125 countries in the 2023 Global Hunger Index (www.globalhungerindex.org) and its level of hunger is characterized as serious in the index. The advantage of focusing on Pakistan is that we can build on previous work by the model teams (Smolenaars et al., 2023) and the availability of high-quality household survey data, which is not always available for developing countries and emerging economies.

The sections below describe the modelling framework, including a short presentation of each of the models, key input data and how they can be linked. Subsequent sections, present base line information on subnational food demand and supply, followed by a short description of next steps.

# Modelling framework

Figure 1 shows the four different models that are combined in our framework and how they are linked. The four models include: (a) MAGNET, a global computable general equilibrium model, (b) the Spatial Simulation of Income Dynamics (SSID) model, (c) The Lund Potsdam Jena Management Land model (LPJmL) and the land use model MAGNETgrid.

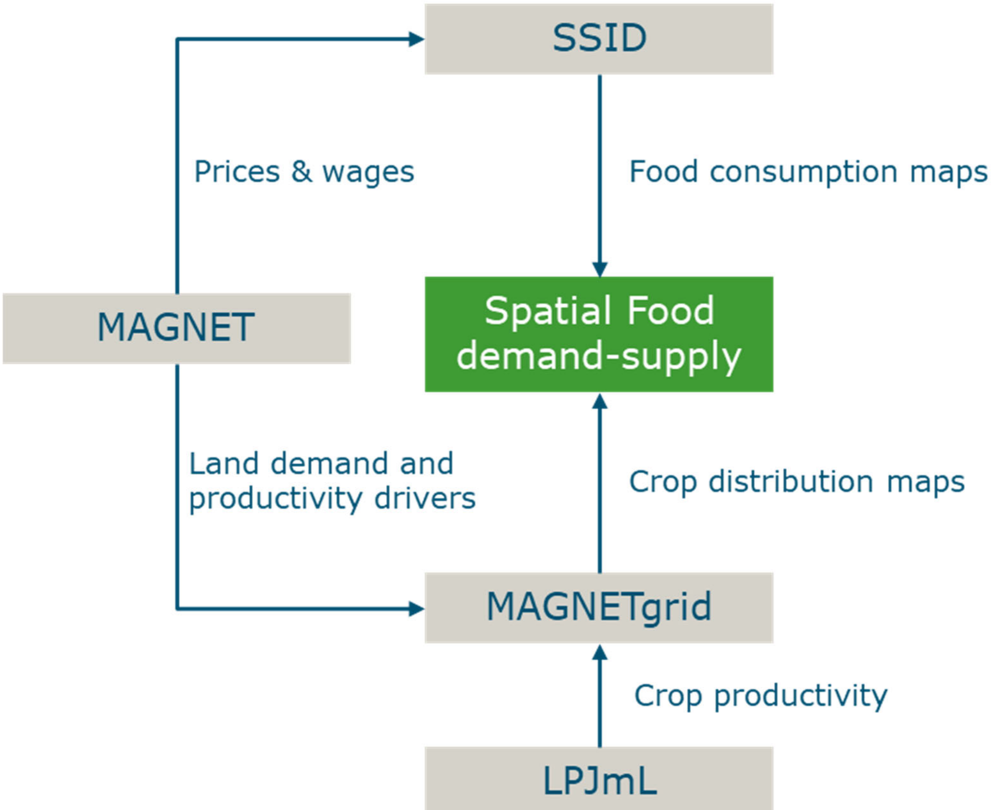


*Figure 1: Multi-model framework to assess subnational food demand-supply gaps.*

## MAGNET

The MAGNET model (Woltjer et al., 2014) is a macro-economic model with global coverage and national level detail. The core of MAGNET is the GTAP model (Corong et al., 2017), with additional features added in a modular fashion which can be chosen by the user to address the specific research question at hand. MAGNET has 114 economic sectors with a particular focus on agriculture, forestry, and the bioeconomy (e.g. bioenergy, biofuels, biomaterials, biobased chemicals). Bilateral trade flows between all countries in the model facilitate the interpretation of global trends in the national level context and similarly place national level polices in a global context. Key variables are GDP, sectoral value added, sectoral production, production factor use\prices, land use, sectoral labour demand and wage changes, commodity prices, and bilateral trade.

The core relationships in the model are payments for goods and services in a closed economic system. The model tracks these value flows as well as the relative changes in price and quantity of these goods. The input data for the payments and receipts for goods and services in the 2014 base year are taken from the GTAP 10 Database (Aguiar et al., 2019), supplemented occasionally with additional databases for extra sectoral detail. The base year is then updated for subsequent periods with scenario projections of GDP (Dellink et al., 2017) and population (KC & Lutz, 2017) taken from the Shared Socio-Economic Pathways (O'Neill et al., 2017). The model then adjusts consumption, production and trade and prices into a new equilibrium for the updated periods.

Further, by matching the core economic flows with outside data sets from the FAO and others the MAGNET model can also report on physical quantities in select sectors, for example food production and consumption in weight and nutritional content (FAO, Food Balances), land use (FAO, Land Use), and irrigation water use (Haqiqi et al., 2016), and greenhouse gas emissions (provided by satellite GTAP databases).

## Spatial Simulation of Income Dynamics (SSID) Model

SSID (Spatial Simulation of Income Dynamics) is a spatial microsimulation model that makes it possible to generate subnational projections of SDG1 (income and poverty) and SDG2 (food consumption, prevalence of undernourishment and diet quality) indicators. The model uses an iterative proportional updating (Ye et al., 2009), to reweigh large-scale income and expenditure surveys to align them with population census information, which is representative for small geographical scales (Tanton, 2014; Williamson, 2013). To project the results into the future, the weights for each region were adjusted using detailed subnational projections for key drivers, including demographic change and occupational structure that are consistent with different scenarios on future national and subnational socio-economic development. To account for the impacts of structural economic change (e.g. technical change and labor market dynamics) on income, the results of household-level income projections are dynamically updated with sectoral- and country- specific wage and food price projections (Hallegatte & Rozenberg, 2017) from MAGNET.

The SSID model was extended to produce projections of food consumption under different socio-economic scenarios. The model uses income elasticities, which describe the relationship between the change in income and the change in food demand, and how they change over time, as well as differences in preferences between urban and rural households for different food groups, to capture the impact of income change and urbanization on the change in food demand. Urbanization, as well as the impact of demographic change on food demand, is also captured by changes in the household weights in the SSID model, which reflect subnational changes in the share of urban and rural population and changes in the distribution of age and sex, in line with the proposed scenarios

*Table 1: Input data for SSID*

| **Data** | **Source** |
|---|---|
| Gridded SSP population projections | Jones and O'Neill (2016) |
| Macro SSP projections | SSP database |
| Gridded population maps | WorldPop |

| | |
|---|---|
| Income elastiticities | IFPRI Income and Price Elasticities of Food Demand (E-FooD) Dataset |
| 2016 Household survey data for Pakistan | Pakistan Statistics |

## LPJmL

The Lund Potsdam Jena Management Land model (LPJmL) simulates the coupled hydrology and carbon cycles. Therefore, it is a suitable model to research the linkages between water availability and food production (Gerten et al., 2011). It runs at 5 min resolution, but the model simulates the daily water balance at a sub-grid scale. Precipitation and irrigation water enter the soil and can take different pathways. Possible pathways are direct surface runoff, subsurface runoff, evaporation from the soil, transpiration by vegetation or infiltration into the groundwater. Twelve crop groups are considered and the modelled yields are calibrated against subnational agricultural statistics (Biemans et al., 2019). The model represents both natural and crop plant functional types (PFTs) that are categorized based on biophysical characteristics. The model furthermore includes a river routing module that calculates river discharge and includes lakes and reservoirs (Biemans et al., 2016; Rost et al., 2008). Reservoirs for both irrigation and other purposes (e.g. hydropower) are included in the model by a simple generic reservoir operation scheme (Biemans et al., 2011).

*Table 2: Input data for LPJmL model on 5 min resolution based on the study of Biemans et al. (2019)*

| **Data** | **Source** |
|---|---|
| Climate historical | HI-AWARE reference dataset (Lutz and Immerzeel, 2015) |
| Climate future | Hi-AWARE future dataset |
| Soil | Harmonized World Soil Database |
| Land use | MIRCA2000 (Portmann et al. (2010)) and adapted by Biemans et al. (2016) |
| Cropping calendar | Biemans et al. (2016) |
| Drainage | HYDROshedS global database at 5 min resolution (Lehner et al. 2008) |
| Reservoirs | GRanD (Lehner et al. 2011) |
| Water demand other sectors | Smolenaars et al. (2021) & Smolenaars et al. (2022) |

## MagnetGrid

MagnetGrid is a model framework that simulates the spatial patterns of agricultural land use resulting from economic decisions on the use of land. It does so by combining future scenario-based projections on the supply, demand, prices and production costs of different agricultural commodities (as simulated by equilibrium models, such as MAGNET and GTAP) with spatially-explicit projections on the biophysical suitability (as simulated, for example, with gridded crop growth models such as LPJmL for agricultural production. Hence, MagnetGrid allows to project and visualize future agricultural land-use change patterns that emerge from climatic and socio-economic developments under a set of conditions that are specified in scenarios. It is able to explicitly simulate the effects of discontinuities such as the emergence of new land-use types (e.g. 2nd generation biofuel crops), the effects of policies affecting the economic performance of production systems (e.g. subsidy schemes, tax reductions/exemptions, removal of trade barriers), and the economic decisions leading to the adoption of innovative agricultural practices.

In its current configuration, MagnetGrid is able to downscale GTAP (Global Trade Analysis Project)-based (Walmsley & Aguiar, 2012) regional projections on the use of land for the production of agricultural commodities, and provide scenario-based map projections of agricultural land-use change, both at the global level and for dedicated case studies at the regional/country level. MagnetGrid applies a probabilistic allocation algorithm, according to which each unit of land (e.g. a regular grid cell) within a region is allocated to a percentage for each simulated land-use type (indicating the share of total area of the grid cell that is used by that land-use type), so that the scenario projections for total aggregated land claims in a region (e.g. as projected by MAGNET) are simultaneously fulfilled for all simulated land-use types. The configuration of the model is based on flexible templates, which allows for different scenario alternatives and configurations (e.g. combination of crop types into sectors, aggregation of countries into simulation regions) can be seamlessly and efficiently accommodated. The original documentation of the model is published by (Diogo et al., 2020) for a detailed description of the theory (Diogo et al., 2015), but an updated and improved global demo version of MagnetGrid is under preparation and it will be disclosed in a R package in 2024.

MagnetGrid makes use of basic input files consisting of global spatial datasets that allows the downscaling MAGNET results to the grid level. These minimum required datasets are described in Table 3.

*Table 3: Description of MagnetGrid basic input spatial data files.*

| **Spatial data input** | | **Original data format** | **Original grid size** | **Source** | **Description** |
|---|---|---|---|---|---|
| Land use maps | Crop-specific distribution maps | Raster | 5 arcmin | (Lamarche et al., 2017; Pesaresi et al., 2016; Ramankutty et | Initial land use maps containing both non-agricultural (NAg) land uses (exogenous in MAGNETGrid, i.e. not dynamically modelled) and crop-specific (including |

| | | | | | |
|---|---|---|---|---|---|
| | | | | al., 2008; You et al., 2014) | pasturelands) distribution maps (endogenous in MAGNETGrid, i.e. dynamically modelled). The latter represents the land baseline year and should be as close as possible to the MAGNET baseline year (i.e. 2014 for the Pakistan case study). Both maps should be available in percentage of land area per grid cell with the same spatial resolution (metric coordinate system), which allows for the quantification of the dynamic of land change. |
| | NAg land uses | Raster | 5 arcmin | (Lamarche et al., 2017; Pesaresi et al., 2016; Ramankutty et al., 2008; You et al., 2014) | |
| Agro-ecological suitability maps | | Raster | 5 arcmin | (Fischer et al., 2021) | Agro-ecological suitability maps are crop-specific biophysical information on crop productivity potential considering both rainfed and irrigated conditions (i.e. with and without water restrictions). |
| Irrigation maps | | Raster | 5 arcmin | (Siebert et al., 2013) | Irrigation maps are key in MAGNETGrid as it informs the location of areas containing irrigated areas. Therefore, it will guide the use of either rainfed or irrigated agro-ecological suitability map for the given region. |
| World administrative division map | | Shapefile | - | | World administrative division map contains the borders of all countries and territories in the world following the ISO 3166 code. This shapefile map will be used to extract the scenario geographical extent of the scenarios and also to align with the MAGNET aggregated regions. |

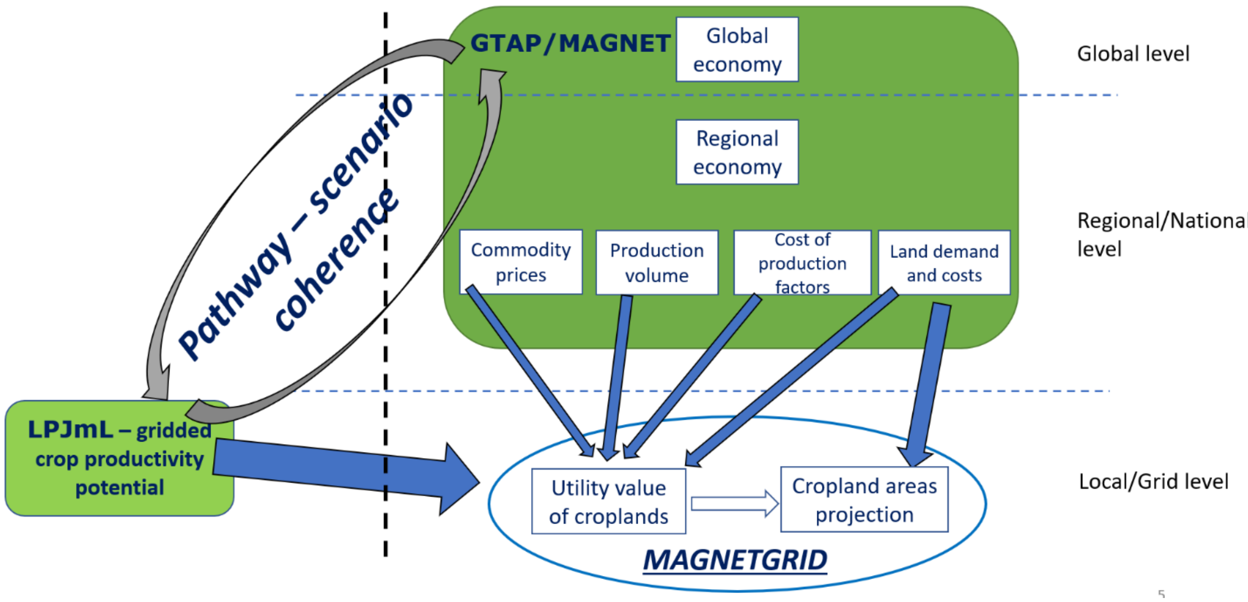


*Figure 2: MagnetGrid's multimodel framework for the simulation of agricultural land-use patterns for regional models, derived from Diogo et al.*(Diogo et al., 2019).

## Integrating LPJml in MagnetGrid: assessing spatio-temporal dynamics of agricultural production costs

For the Pakistan case study, crop productivity potentials from LPJmL for rainfed and irrigated crops are provided to MagnetGrid and further used to calculate the agricultural production costs and their utility value (see figure 2 above). The crop productivity potentials are calculated at a 5 arc-minute resolution (Smolenaars, 2023) for the Indus Basin, which aligns with the spatial resolution of the global version of MagnetGrid. LPJmL runs at a daily timestep, but the output for this purpose is provided as yearly averages. The crop productivity potentials are calculated using climate projections and availability of water resources for irrigation. For this, both surface water (in lakes and reservoirs) and groundwater resources are included. Besides water use for irrigation, projections of water withdrawals and consumption for electricity, industries and households are also affecting water availability. These demands are currently based on IMAGE SSP2 projections (Bijl et al., 2018).

To enable the utilization of LPJmL crop productivity potentials in MagnetGrid, we firstly harmonized all the crop types of MagnetGrid and LPJmL into the aggregated GTAP crop types, which are simulated by MAGNET (see table 4). This is crucial because LPJmL and MagnetGrid are independent from each other, with different goals and different levels of granularity regarding crop types. As an intermediate step, we conducted a spatially explicit cost-benefit analysis per crop sectors by combining MAGNET agro-economic results (e.g. capital value, land prices, labor value, production output, land demand) per crop sector and LPJmL based crop yields at grid level.

*Table 4: Harmonization of MagnetGrid crop definitions and LPJmL crop definitions to be used in the Pakistan case study.*

| **Specific aggregation of LPJmL crop types for the Pakistan case study (based on Smolenaars, 2023)** | **Simulated crop types for the Pakistan case study (aligned with GTAP/MAGNET sectors)** | **General aggregation of MagnetGrid crop types [ref] with GTAP/MAGNET crop types** |
|---|---|---|
| Sugarcane | Sugarcane (c_b) | Sugarcane and sugarbeet |
| Pasture and biomass grass | Grazing grasslands (ctl) | Pasture |
| Maize and tropical cereals | Cereals (gro) | Maize, other cereals, pearl millet, small millet and sorghum |
| Temperate cereals | Wheat (wht) | Wheat, barley |
| Other crops | Other crops (ocr) | Arabica coffee, cocoa, robusta coffee, tea and tobacco |
| Soybean, rapeseed, groundnut and sunflower | Oil seed crops (osd) | Coconut, groundnut oil, palm, olive oil, rapeseed, sesame seed, soybean and sunflower |
| Rice | Paddy rice (pdr) | Rice |
| Pulses, tropical roots and temperate roots | Vegetables and Fruits (v_f) | Banana, bean, cassava, chickpea, cowpea, lentils, other pulses, other roots, pigeon pea, plantain, potato, sweet potato, temperate fruits, tropical fruits, vegetables and yams |

# Preliminary results

## Base year food supply maps

Figure 3 shows an example of intermediate results from the MagnetGrid model based on combining capital value, land prices, labor value, production output and land demand per crop sector with spatially explicit crop yields from LPJmL.  The maps show the spatial distribution of land economic returns of the cereals sector in 2014 (baseline) and 2050. The economic returns of all crop sectors are subsequently combined with the base year distribution of crops and projected growth in yield and production to create crop distribution maps into the future.

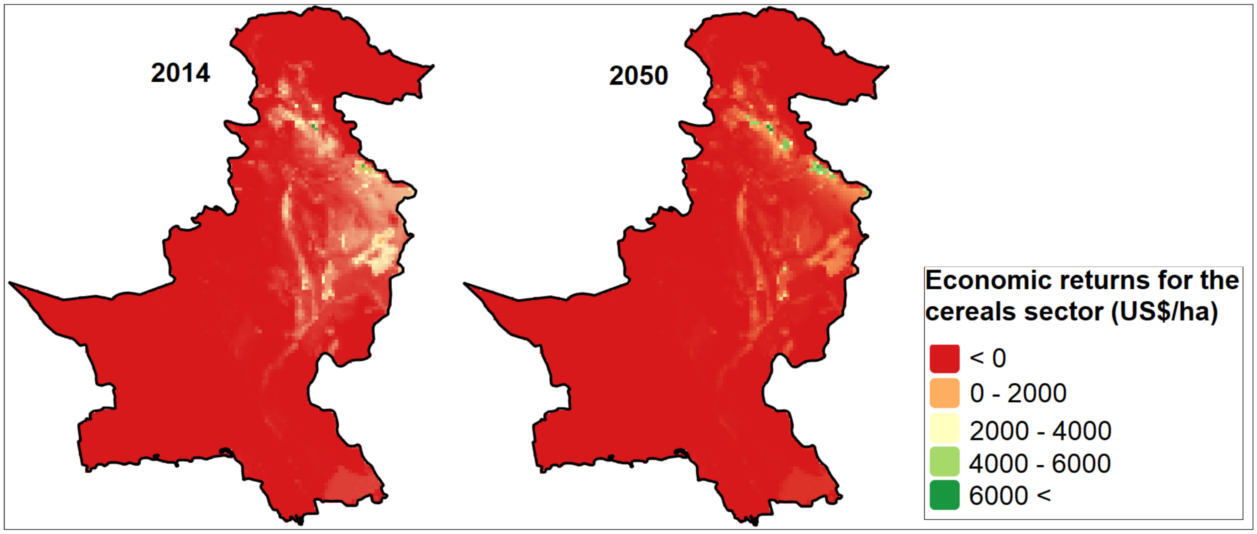


*Figure 3: Spatial distribution of land economic returns of the cereals sector in 2014 (baseline) and 2050 in Pakistan.*

Figure 4 shows the LPJmL base year maps for the tree largest crop groups in terms of irrigated crop production. All three groups are cultivated along the Indus River. Temperate cereals show a high production in the Punjab province. Moreover, there is some cultivation of temperate cereals in Balochistan, a province with little to no agricultural activity. High production of sugar cane is found more to the West in the province of Khyber Pakhtunkhwa. Rice production is almost equal along the river and does not show higher production in any particular area.

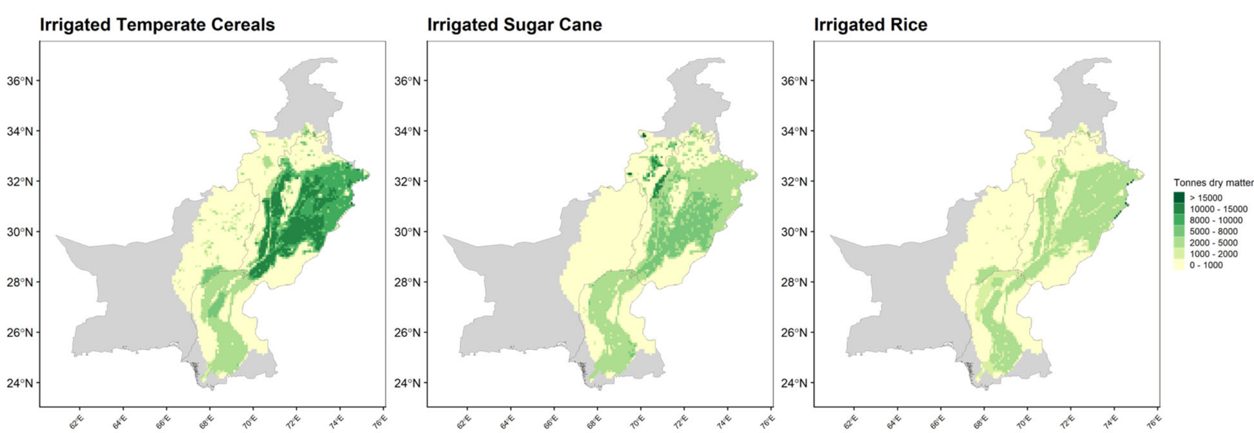


*Figure 4: The production in tonnes dry matter in Pakistan visualized for the three largest crop groups in terms of production, from left to right: temperate cereals, sugar cane and rice. The grey areas are the grid cells without data. Both figures are for the year 2008.*

Figure 5A shows the spatial distribution of total food production in Pakistan, which is the highest in the North-to-middle East. This is the Punjab province where most of the irrigation canals are built. There is no data available for the province of Balochistan and the northern areas of Pakistan.

However, as a result of the climate conditions in these regions there is little to no agricultural, related to crops production, activity. The crop group temperate cereals has the largest share of total agricultural crop production, followed by sugar cane and rice (Figure 5B). In the same figure it is shown that most production is taken place on irrigated fields in Pakistan.

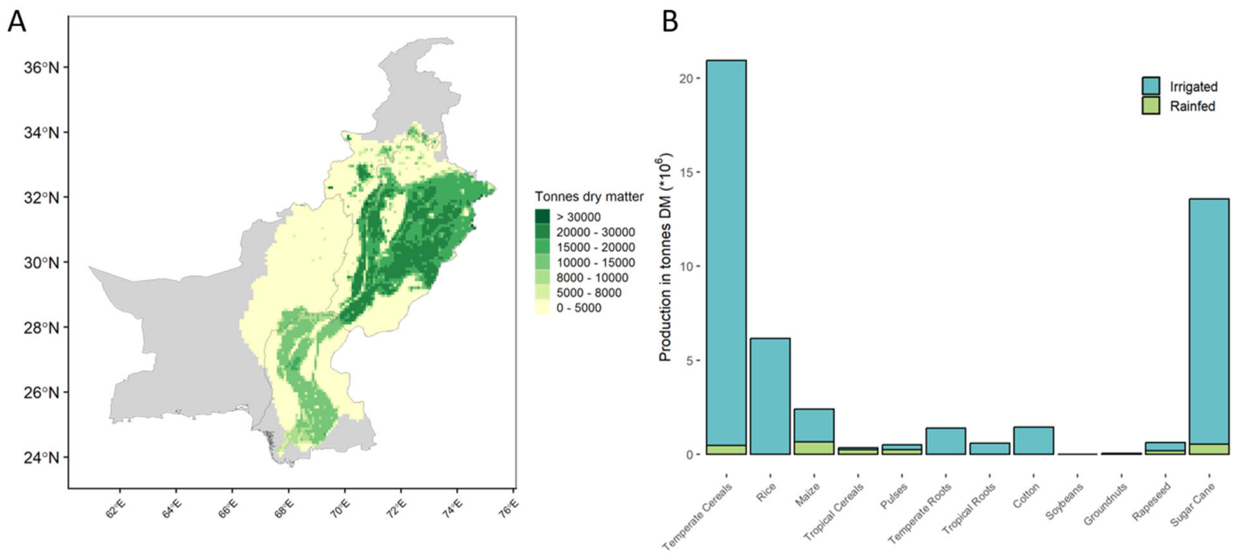


*Figure 5: The total food production in tonnes dry matter in Pakistan visualized in space per grid cell (A) in which the grey areas are the grid cells without data. Figure B shows the production per crop for both irrigated and rainfed. Both figures are for the year 2008.*

## Base year food demand maps

We processed the 2016 national household survey of Pakistan to obtain information on the national diet. Figure 6 shows the composition of the diet, distinguishing between 17 major food groups in gram/cap/day. The dominant food groups in the Pakistan diet are wheat (28%) followed by dairy (22%) and vegetables (14%). In contrast with neighbouring countries India and Bangladesh, the share of rice in daily consumption is much lower Pakistan (3%).

Figure 7 shows the spatial distribution of the consumption of the three major production crops in Bangladesh: wheat, sugar and rice. A first look at the maps, indicates that wheat consumption is highest in the Punjab area, where also most production is located. Nonetheless, the maps also show consumption of wheat and the two other crops in the regions for which there is not production information due to very limited agricultural activity. A proper comparison between food demand and supply, which is planned for the next phase, will involve accounting for population density in all regions to estimate total food demand in tonnes.

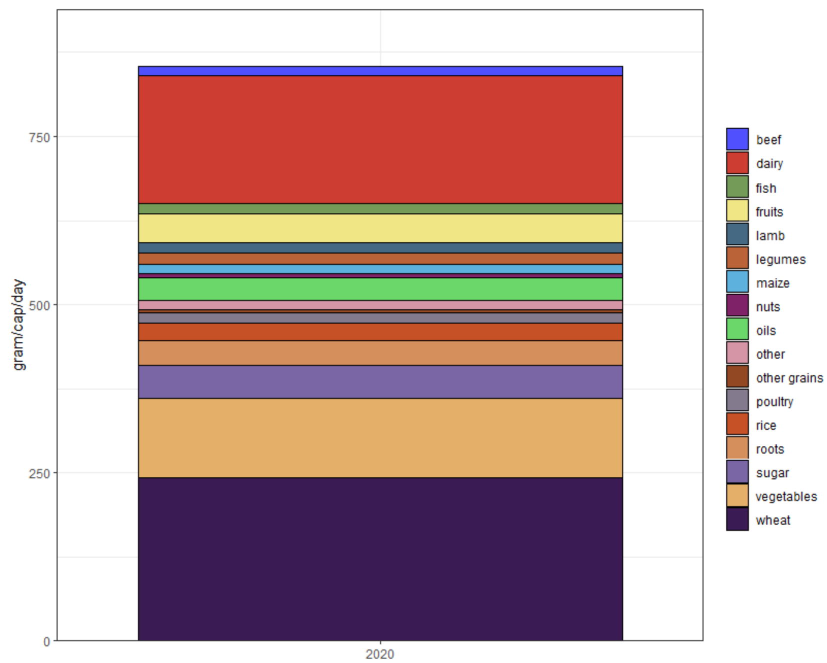


*Figure 6: Pakistan diet (gram per capita per day), 2016.*

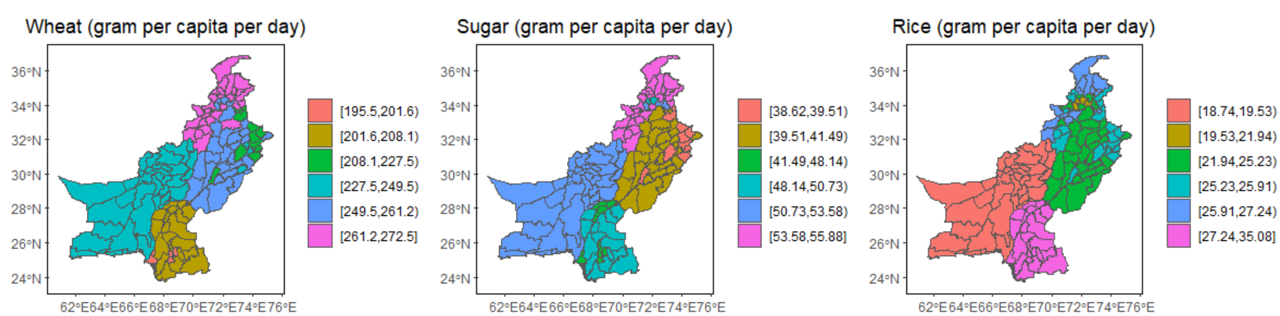


*Figure 7: Food consumption (gram/cap/day) for three major production crops at the subnational level for the year 2020.*

## Next steps

This document presented an innovative modelling framework that makes it possible to assess future trends in food demand and supply at the spatial and subnational level. We provided an overview of the four core models: MAGNET, SSID, MagnetGrid and LPJmL, how they will be linked and the main data sources that will be used as input for the models. We used 2023 KB funding to develop (SSID and MagnetGrid) and improve (MAGNET and LPJmL) the core models, design the modelling framework and collect and process data that is specific to our case-study Pakistan. We also started to calibrate the models to the case-study datasets and to produce base year food demand and supply maps, which were presented above.

In the first half of 2024, we aim to implement the modelling framework and assess future subnational changes in food demand and supply in Pakistan under different socio-economic and climate scenarios. In line with existing global climate and food security assessments, we will combine the Shared Socio-economic Pathways (SSPs) (van Vuuren et al., 2017) and the Representative Concentration Pathways (RCPs) (van Vuuren et al., 2011) to evaluate the impact of a wide range of different socio-economic and climate futures on subnational food security in Pakistan. The first step in our analysis will be to harmonize/scale all input data across the models so food demand, supply and waste are consistently measured. After this base year subnational food demand and supply can be compared in tonnes or gram per capita. In the next step, the same scenarios will run in all models to produce projections of food demand and supply up to 2050 at grid and subnational level. Finally, the results will be analyzed and written up in a working paper.

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