Estimating Cropland Requirement in Global Food System Scenario Models

Supplementary Material 1

1. Mathematical implementation

The following describes the mathematical methodology used to forecast cropland requirement under scenarios with increased or decreased crop production, or productivity gains.

The 2018 production of each commodity crop is characterized by three coefficients: the total production (P_{ref}), the total land area harvested (L_{ref}), and the midpoint offset (O_{50}). This last parameter is the difference between the land area required for production of 50% of the crop at the average yield and the area required for the same amount of production at HY (L_{50}):

$$O_{50} = \frac{L_{ref}}{2} - L_{50}$$

1.1. Land use changes without productivity gains

The cropland requirement estimates for a scenario without any productivity gain are calculated as follows. Let P_i be the total crop production in a newly defined scenario, i.

Expected requirement for scenario i: $L_{i,exp} = \frac{P_i}{P_{ref}} L_{ref}$

This is simply a proportional increase or decrease in cropland requirement scaled to the proportional increase in decrease in production.

Upper bound requirement for scenario i: $L_{i,upper} = L_{i,exp} + \frac{(2O_{50} \times min\{P_i, |P_{ref} - P_i|\})}{P_{ref}}$

Lower bound requirement for scenario i: $L_{i,lower} = L_{i,exp} - \frac{(2O_{50} \times min\{P_i, |P_{ref} - P_i|\})}{P_{ref}}$

Figures S1 and S2 show these values graphically, using wheat production as an example.

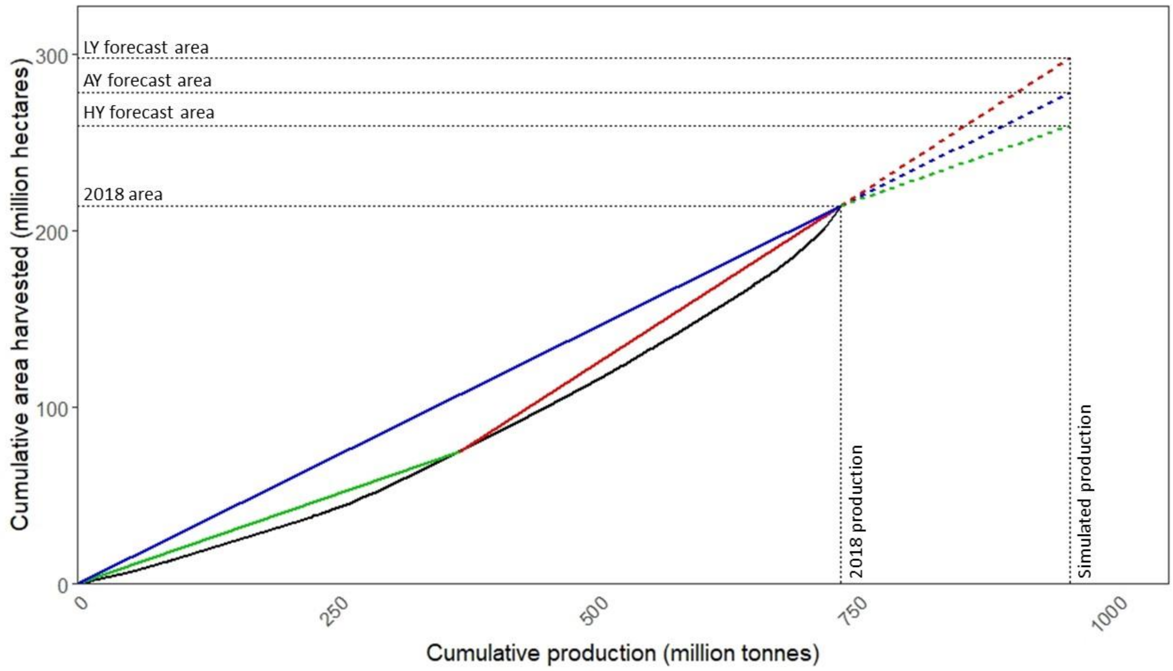

Figure S1. The prediction of required cropland to support a 30% increase in wheat production. The black yield curve shows global production of wheat against land area, with data ordered from best yielding production to poorest yielding. The estimated requirement is calculated using the global average yield (AY, blue). The upper (red dashed) and lower bounds (green dashed) are calculated using the yields of the poorest (LY) and best (HY) yielding 50% of production, respectively. HY (solid green line) and LY (solid red line) trajectories are also shown.

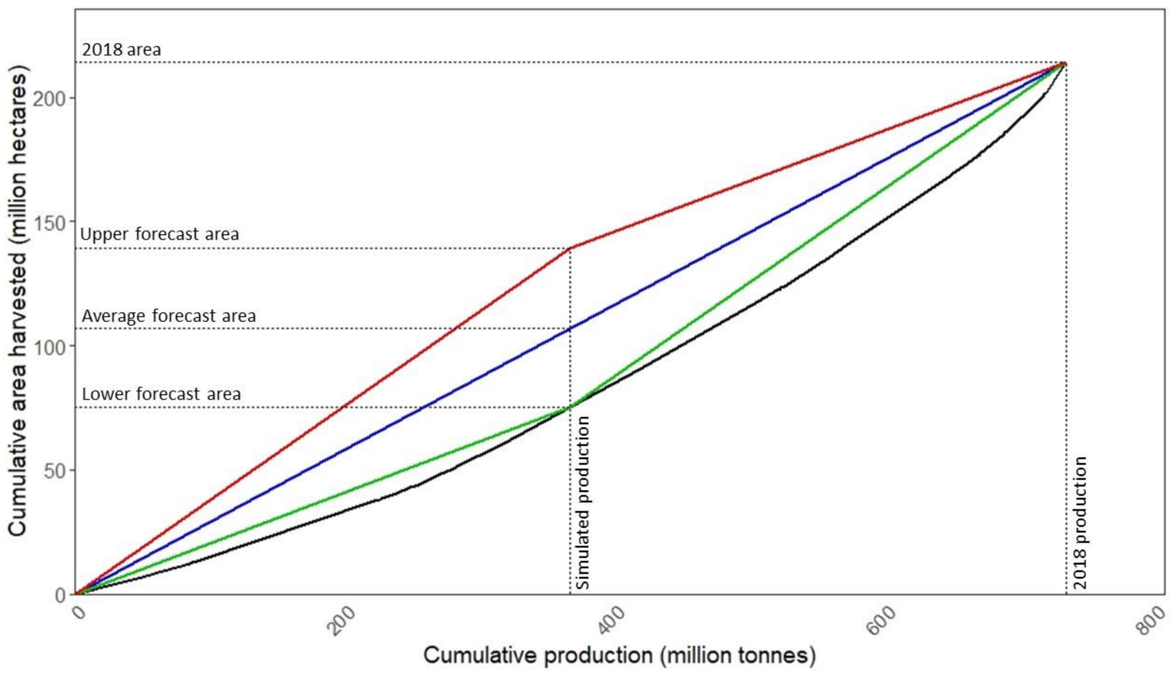

Figure S2. Similarly to Figure S1, here is shown the estimated land requirement, with upper and lower bounds, for a 50% decrease in wheat production. The average forecast area is simply scaled along the average yield line (blue). The lower bound (green) assumes the optimistic case that decreases in production occur on poor yielding land first, down to 50% of 2018 production, and high yielding land *for any further decreases. The upper bound (red) assumes decreases down to 50% of 2018 production occur on high yielding land, and low yielding land for any further decreases.*

1.2. Land use changes with productivity gains

If productivity gains are included in the calculation, the equations to calculate cropland requirement are further elaborated. It is also necessary to define some new variables.

$$O_{25} = \frac{L_{50}}{2} - L_{25},$$

where $L_{25}$is the cropland area required by the highest yielding 25% of production.

Let R_i be a value between 0 and 1 for the proportion of LY production that is improved to HY.

Then, define:

$$Base_i = L_{ref} - 2R_iL_{50}$$

$$Offset_i = (1 - R_i)L_{50} + 2R_iL_{25}$$

$$Limit_i = 2 \times Offset_i \times \frac{min\{P_i, |P_{ref} - P_i|\}}{P_{ref}}$$

The calculated cropland requirement values are then:

Expected requirement for scenario i: $L_{i,exp} = \frac{P_i}{P_{ref}} \times Base_i$

Upper bound requirement for scenario i: $L_{i,upper} = L_{i,exp} + \ Limit_i$

Lower bound requirement for scenario i: $L_{i,lower} = L_{i,exp} - \ Limit_i$

Note that if $R_i = 0$, the above calculated requirement equations are identical to those in section 1.1 for land use changes without productivity gains.

Figure S3 shows a graphical example of the productivity gains approach for wheat, with $R_i = 1$.

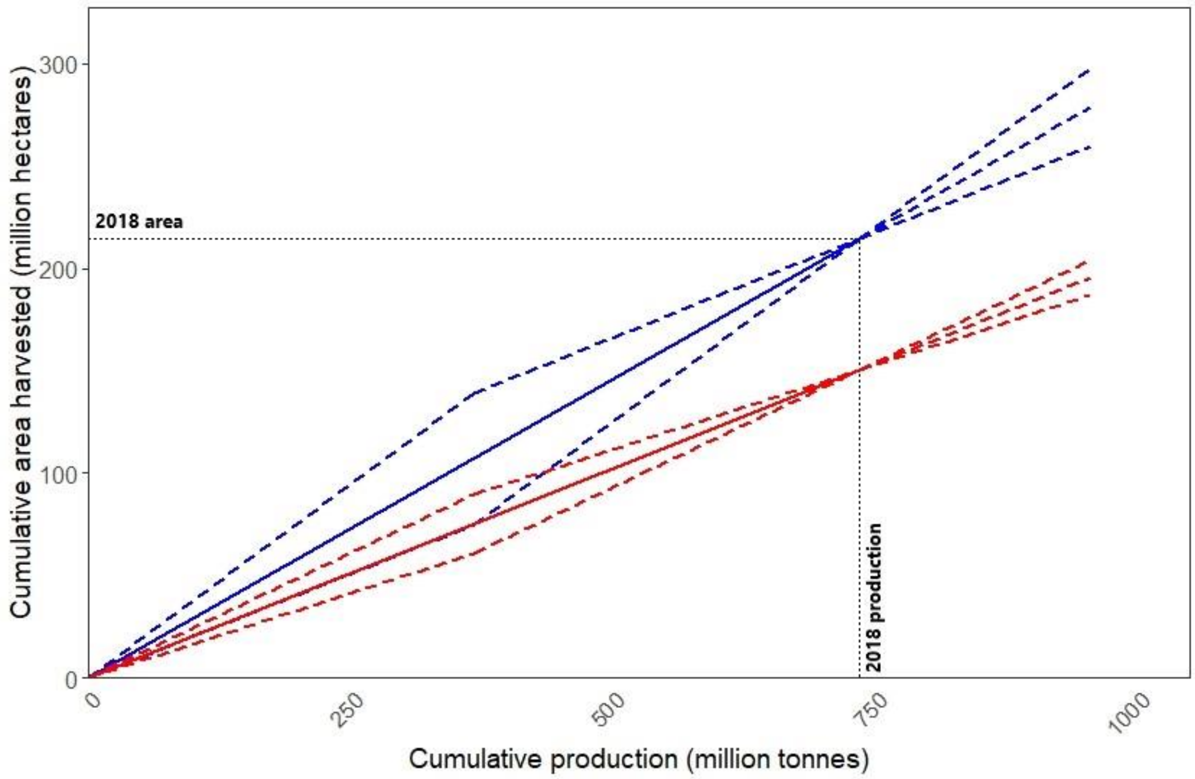

Figure S3. Current global wheat production is represented in blue here: the solid line shows current average global yield; the dashed lines below the 2018 area line indicate LY and HY; the dashed lines above the 2018 area line indicate the predicted cropland requirement of increases in wheat production. In red are shown the same values, under the assumption that 100% of production at LY is improved to HY productivity.

Table S1. Mathematical notation and definitions	
	Fixed parameters
P_{ref}	Production in tonnes of a crop in 2018
L_{ref}	Area harvested in hectares of a crop in 2018
L_{50}	Area required to produce 50% of P_{ref} at HY
L_{25}	Area required to produce the highest yielding 25% of production
O_{50}	Midpoint offset
O_{25}	Upper quartile offset
	User inputs
P_i	Production in tonnes of a crop in scenario i
R_i	Productivity gain value: a value in the range 0 to 1 indicating the proportion of LY production that is improved to HY
	Calculated parameters
$L_{i,exp}$	Expected cropland requirement for scenario i
$L_{i,upper}$	Upper bound cropland requirement for scenario i
$L_{i,lower}$	Lower bound cropland requirement for scenario i
$Base_i$	Calculated values for use in cropland requirement estimation for scenarios where $R_i \neq 0$
$Offset_i$	
$Limit_i$	

2. Example cropland allocation to final use

Below is a worked example of the allocation of total cropland area for a single crop to the final uses of: food, animal feed, and other uses.

Assume 100 tonnes of wheat are harvested from 50 hectares of land. The FAO food balance sheets (FBS) assign the following allocations to this 100 tonnes:

Allocation	**Tonnes**
Seed	1
Losses	5
Food	10
Feed	30
Other uses	10
Processing	44

Seed and losses are assumed implicit in the production of wheat for food, feed, and other uses, so are ignored in further calculations. Thus, the proportional split of wheat to the remaining allocations is:

Allocation	**Proportion of total**
Food	10/94 = 0.106
Feed	30/94 = 0.319
Other uses	10/94 = 0.106
Processing	44/94 = 0.468

Assume all wheat processing is to wheat flour in the FBS, and that a resulting 30 tonnes of wheat flour is assigned the following FBS allocations:

Allocation	**Tonnes**		**Proportion of total**
Seed	0	Assuming seed and losses are implicit…	
Losses	2		
Food	24		24/28 = 0.857
Feed	1		1/28 = 0.036
Other uses	3		3/28 = 0.107
Processing	0		0/28 = 0.000

The final proportion of wheat allocated to food is thus:

Wheat allocated to food + (Wheat allocated to processing x Wheat flour allocated to food)

And similarly for feed and other uses. The worked calculation is as follows:

Allocation	**Proportion of total**
Food	0.106 + (0.468 x 0.857) = 0.507
Feed	0.319 + (0.468 x 0.036) = 0.336
Other uses	0.106 + (0.468 x 0.107) = 0.156

These allocations can be applied to the 50 hectares of wheat harvested, to give the following cropland allocation:

Allocation	Hectares
Food	25.4
Feed	16.8
Other uses	7.8

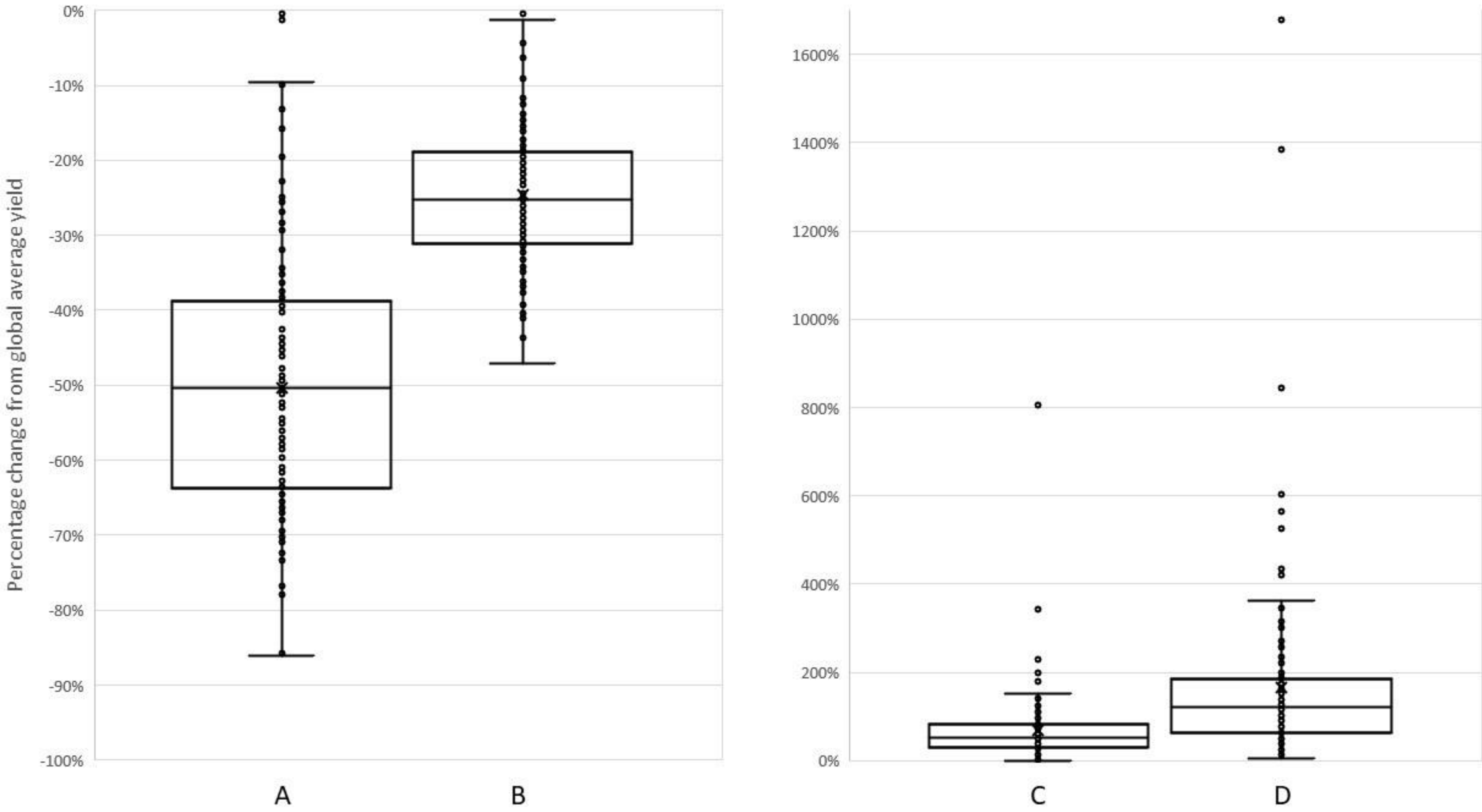

Figure S4. Variation in yield of individual crops. The circles show, for each crop, the percentage change between the global average yield and A) the yield of the poorest performing 10% of production; B) the yield of the poorest performing 50% of production; C) the yield of the best performing 50% of production; D) the yield of the best performing 10% of production. The X symbol denotes the mean value; boxes show the median and interquartile range; range bars show the minimum and maximum values, excluding outliers that are more than 1.5 times the interquartile range below or above the first or third quartile, respectively.