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# Supplementary Materials for

## Metrics for land-scarce agriculture

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Materials and Methods
Supplementary Text
Figs. S1 to S6
Table S1
References

**Other Supplementary Material for this manuscript includes the following:**
(available at www.sciencemag.org/content/349/6245/page/suppl/DC1)

Excel spreadsheets are included for each figure and table as follows:

Fig. 1A – Data, sources, and calculations for computing fraction DRI/100 g of cereal from 1961 to 2012 for global production

Fig. 1B, figs. S6a, S6b, and S6c – Data, sources, and calculations for computing nutritional yields from 1961 to 2012 for world (worksheet 1), India (worksheet 2), China (worksheet 3), and LDCs (worksheet 4)

Fig. S1 – Data and source for share of dietary energy supplied from cereals, roots, and tubers from 1987 to 2011

Fig. S2 – Data and sources for area and production of 8 cereals from 1961 to 2013 for world (worksheet 1), India (worksheet 2), China (worksheet 3), and LDCs (worksheet 4)

Fig. S3 – Data, sources, and calculations for computing fraction DRI/100 g of eight cereals

Fig. S4 – Data, sources, and calculations for computing fraction of production used for food for world (worksheet 1), India (worksheet 2), China (worksheet 3), and LDCs (worksheet 4)

Fig. S5a – Same as spreadsheet for Fig. 1A for India

Fig. S5b – Same as spreadsheet for Fig. 1A for China

Fig. S5c – Same as spreadsheet for Fig. 1A for LDCs

Table S1 – Data, sources, and calculations for computing sensitivities of nutritional content of cereals to changes in mixes of cereal types and diversion to feed for world (worksheet 1), India (worksheet 2), China (worksheet 3), and LDCs (worksheet 4)

Fig. S4 – Data, sources, and calculations for computing fraction of production used for food for world (worksheet 1), India (worksheet 2), China (worksheet 3), and LDCs (worksheet 4)

Fig. S5a – Same as spreadsheet for Fig. 1A for India

Fig. S5b – Same as spreadsheet for Fig. 1A for China

Fig. S5c – Same as spreadsheet for Fig. 1A for LDCs

Table S1 – Data, sources, and calculations for computing sensitivities of nutritional content of cereals to changes in mixes of cereal types and diversion to feed for world (worksheet 1), India (worksheet 2), China (worksheet 3), and LDCs (worksheet 4)

## Materials and Methods

### Methods

The example of changes in nutritional composition of the global cereal supply is calculated from the eight most pervasive cereal types (grown on >5 million hectares in 2013). These include barley, maize, millet, oats, rice, rye, sorghum, and wheat. The examples of India, China, and Least Developed Countries include all eight cereals (except oats and rye in India and LDCs due to limited production).

### Derivation on Nutritional Yields

We propose a metric that incorporates measures of two important dimensions for future food systems: the production of nutritious food and efficient use of land. This metric, termed "nutritional yield", is quantified as follows:

$$NY_{ij} = \text{fraction of } DRI_i/100g_j \times \text{tonnes}_j/\text{ha/year} \times 10^4/365$$

where tonnes are metric tons,

$NY_{ij}$ = nutritional yield of nutrient *i* from food item *j* in units of fraction of $DRI_i$/ha-year

Fraction of $DRI_i/100g_j$ = fraction of daily dietary reference intake of nutrient *i* provided by 100 grams of food item *j*, calculated as $(g_i/100g_j)/DRI_i$. We use values for nutrient composition of different food items ($g_i/100g_j$) from the U.S. Department of Agriculture (*1*) and United Nations International Network of Food Data Systems (*2*) as applied in (*3*). For $DRI_i$, we use average dietary reference intake values for RDA (recommended daily allowance) for males and females (not pregnant or lactating) aged 19 to 50 for micronutrients (iron and zinc) (*4*), protein (*5*), and energy (*6*). The metric could be adjusted for other age groups and life stages.

$\text{tonnes}_j$/ha/year = metric tons of food item *j* produced per hectare per year (the traditional yield measure)

$10^4/365$ = unit conversion

## Supplementary Text

### Limitations

This analysis has several limitations. It includes the nutrient content of different cereals but does not include the bioavailability in the human body, which is generally lower than the nutrient content. Moreover, bioavailability of nutrients varies among cereals and other sources for micronutrients, which could be taken into account in comparisons of nutritional yields. We also do not differentiate among different amino acids in protein content, nor do we take account of the fact that nutrient content can vary within a cereal type depending on soil, growing conditions and varieties, and management. Nutritional yield is based on production at the farm level and does not account for loss of cereals available for consumption through waste and processing. The calculation of DRI is based on recommendations for adult males and females and does not consider other age and life-stage groups. For example, requirements are higher for pregnant and lactating females and lower for children. The metric could readily be calculated for these other groups. The metric can also be calculated for nutrient composition for different items and from different datasets, though we note the lack of a standard database for the nutrient composition of food items consumed in different countries.

Nutritional yield is one metric to measure efficiency of land area. Other measures can also be relevant for decisions about which crops to promote. For example, nutrients per calorie could be important in the context of rising obesity around the world (*7*). Measures of nutrients produced in relation to other resources, such as water or nitrogen, could be important where those resources are in short supply. The relevant metrics depend on the objectives for food production in different settings.

The example based on the global supply of cereals is for illustrative purposes. In reality, people do not consume a mix of globally-produced cereals. In addition, people also obtain nutrients from other food items in addition to cereals.

**Fig. S1**

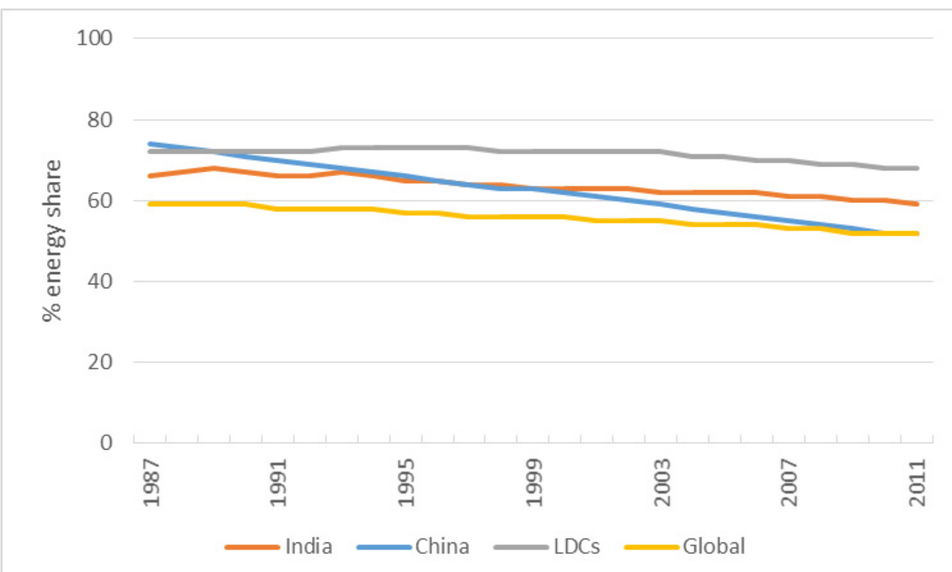
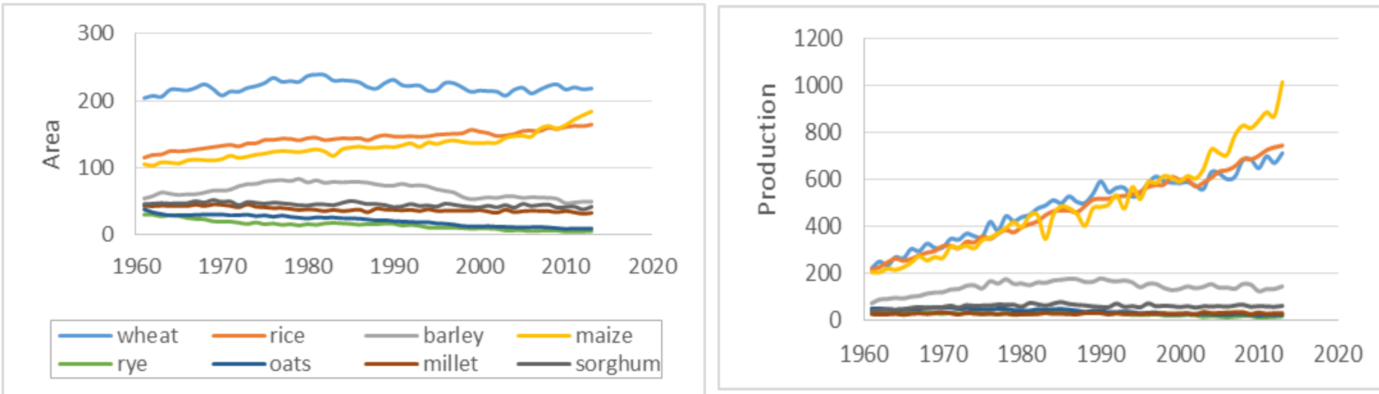


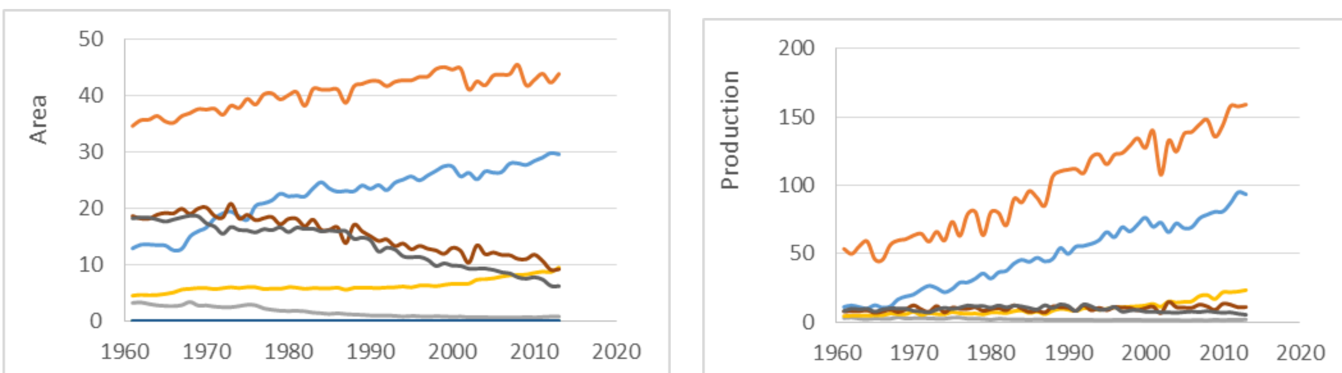

**Fig. S1. Share of dietary energy supply derived from cereals, roots and tubers (%) (3-year average).** Data from (*8*). See Fig. S1 Excel spreadsheet for details.

**Fig. S2**

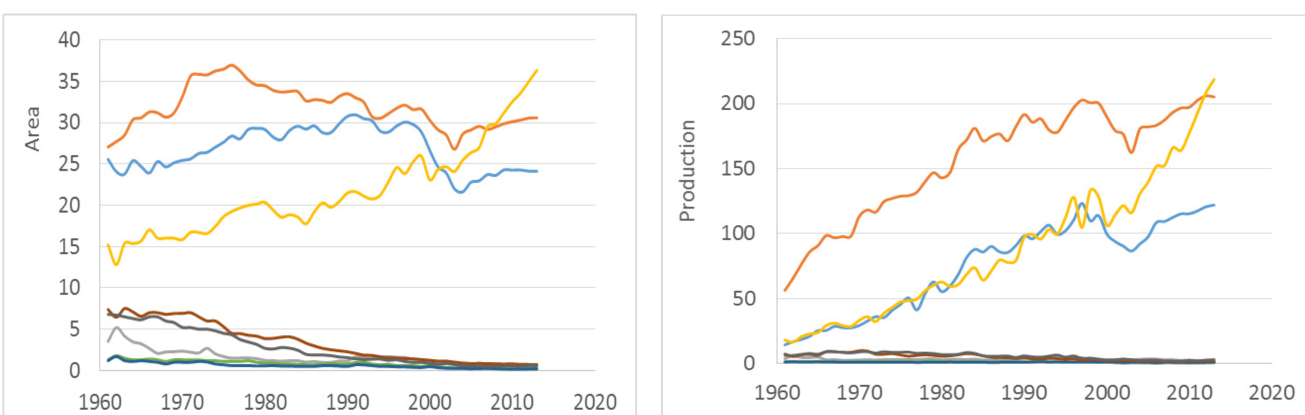
a)


Area
Production
300
200
100
0
1200
1000
800
600
400
200
1960
1970
1980
1990
2000
2010
2020
wheat
rice
barley
maize
rye
oats
millet
sorghum

b)


Area
Production
50
40
30
20
10
0
200
150
100
50
1960
1970
1980
1990
2000
2010
2020

c)


Area
Production
40
35
30
25
20
15
10
5
0
250
200
150
100
50
1960
1970
1980
1990
2000
2010
2020

d)

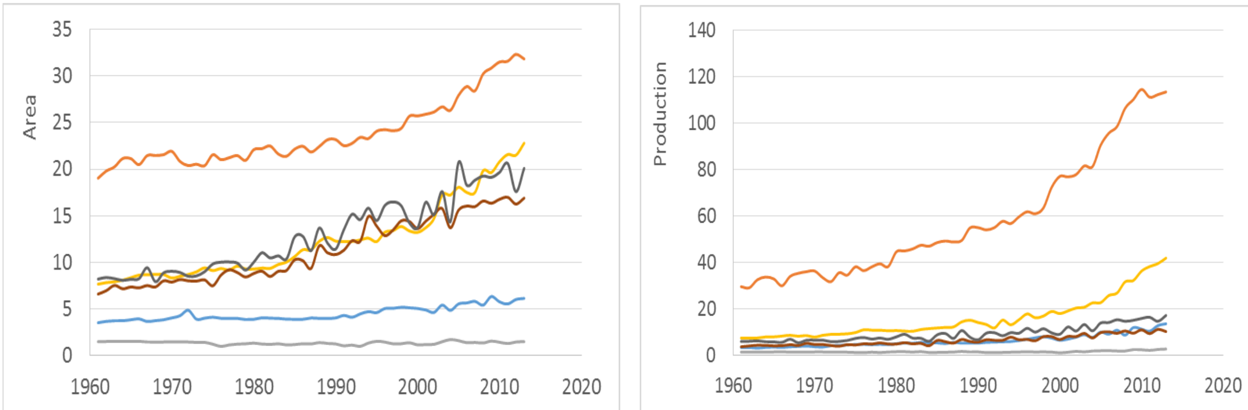



**Fig. S2. Area and production of cereals by geographical areas.** (**a**) Global area (left) and production (right) of cereals from 1961 to 2013. Total cereal area increased approximately 5% between the decades of the 1960s and 2000s. Data from (*8*). (**b**) same as (a) for India. (**c**) same as (a) for China. (**d**) same as (a) for Least Developed Countries. Area is in units of million hectares and production in million tonnes/year. Note differences in scales. See Fig. S2 Excel spreadsheet for details.

**Fig. S3**

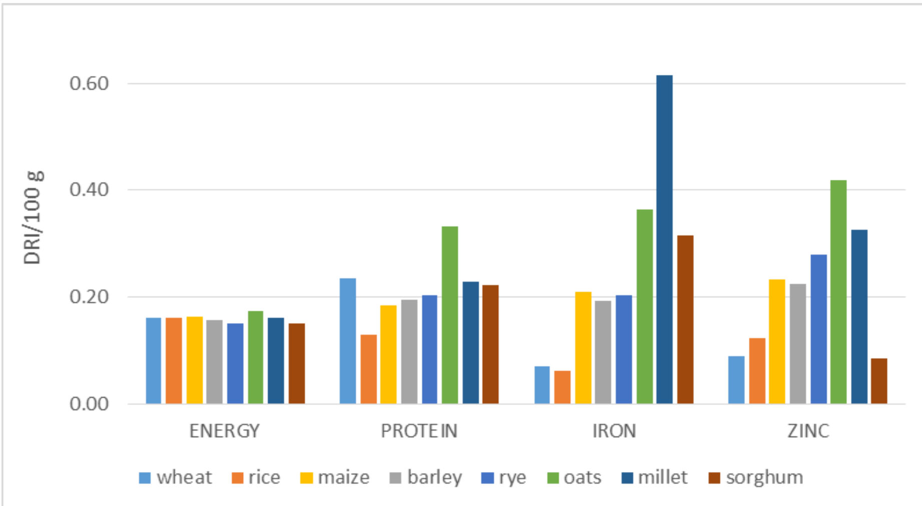
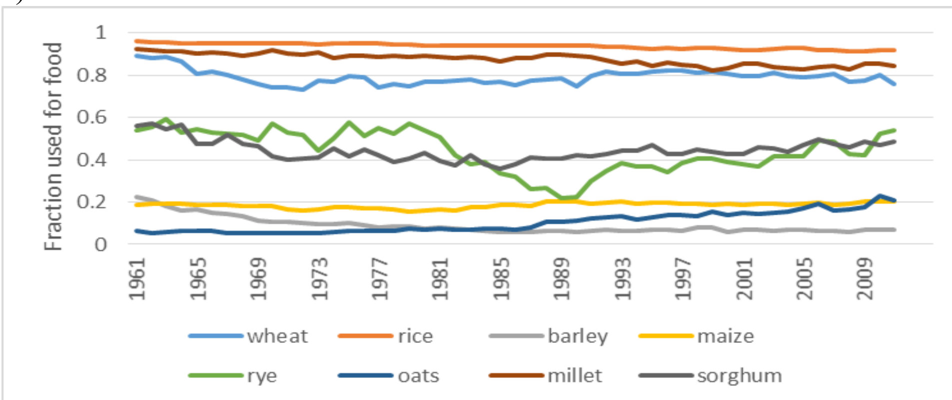



**Fig. S3. Nutritional content for energy, protein, iron and zinc for eight cereals from (*9*).** In reality, the nutritional content would vary with growing conditions, soils, management, and variety. See Excel spreadsheet for Fig. S3 for details.

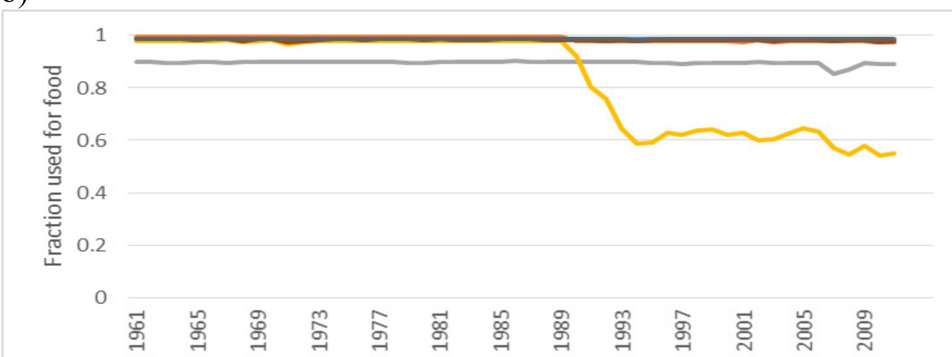
**Fig. S4**

a)



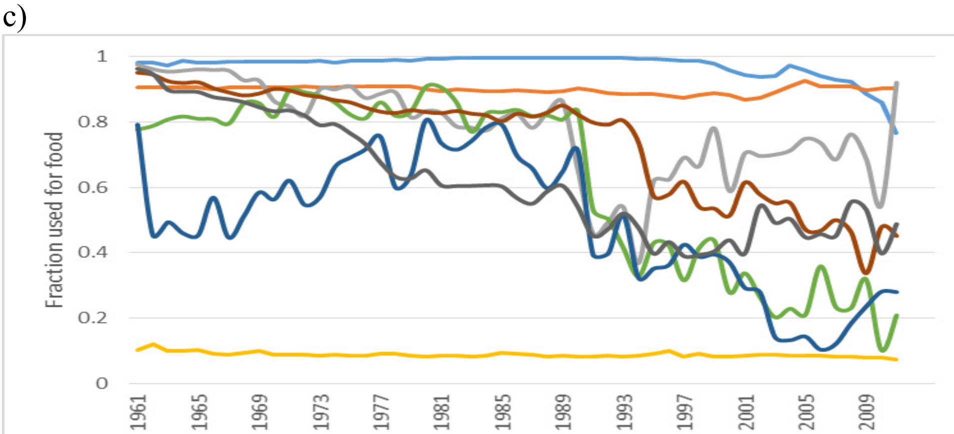
Fraction used for food
1
0.8
0.6
0.4
0.2
0
1961
1965
1969
1973
1977
1981
1985
1989
1993
1997
2001
2005
2009
wheat
rice
barley
maize
rye
oats
millet
sorghum


b)



Fraction used for food
1
0.8
0.6
0.4
0.2
0
1961
1965
1969
1973
1977
1981
1985
1989
1993
1997
2001
2005
2009


c)



Fraction used for food
1
0.8
0.6
0.4
0.2
0
1961
1965
1969
1973
1977
1981
1985
1989
1993
1997
2001
2005
2009

d)

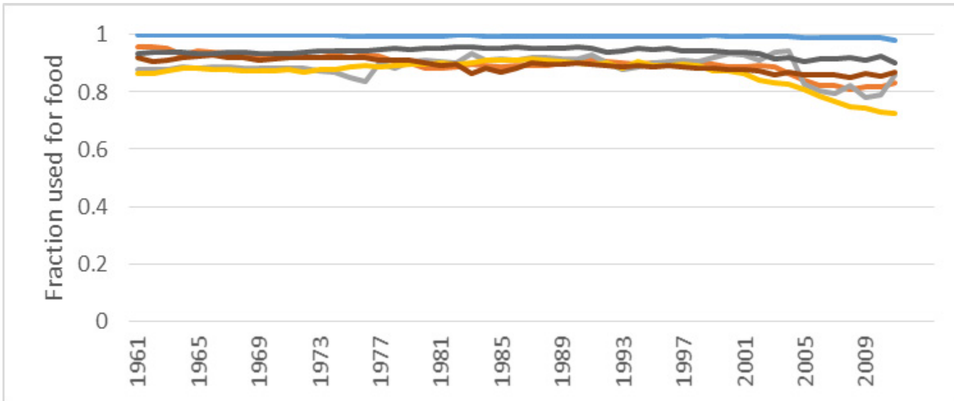
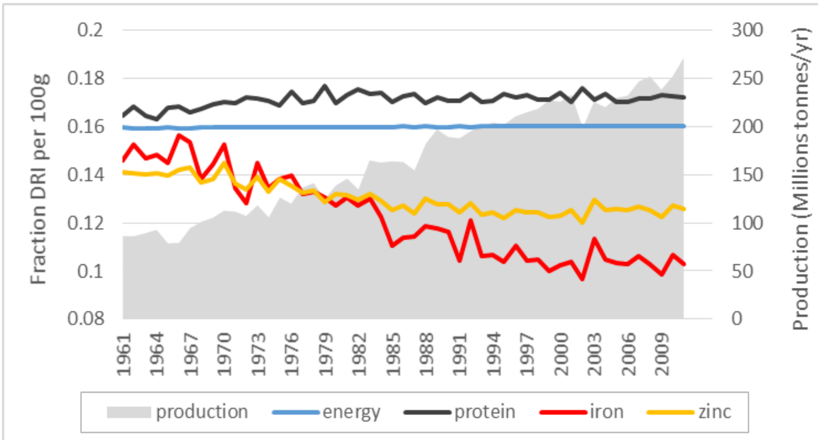



**Fig. S4. Fractions of cereals used for food.** Calculated from the ratio of food to food plus feed from food balance sheets in (*8*). a) global supply, b) India, c) China, and d) Least Developed Countries. See Fig. S4 Excel spreadsheet for details.

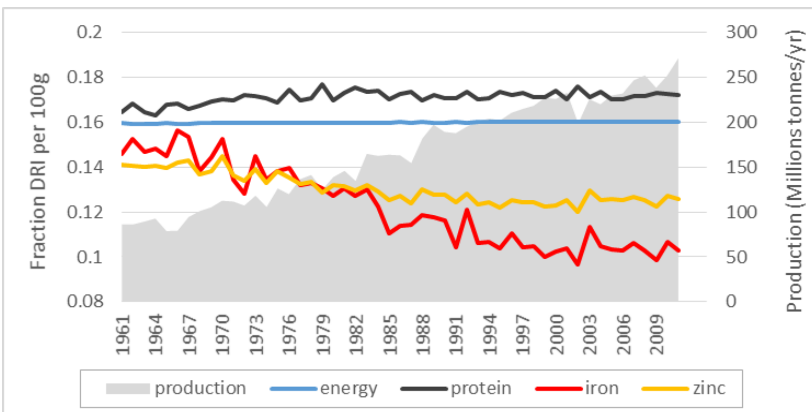
**Fig. S5**

a)



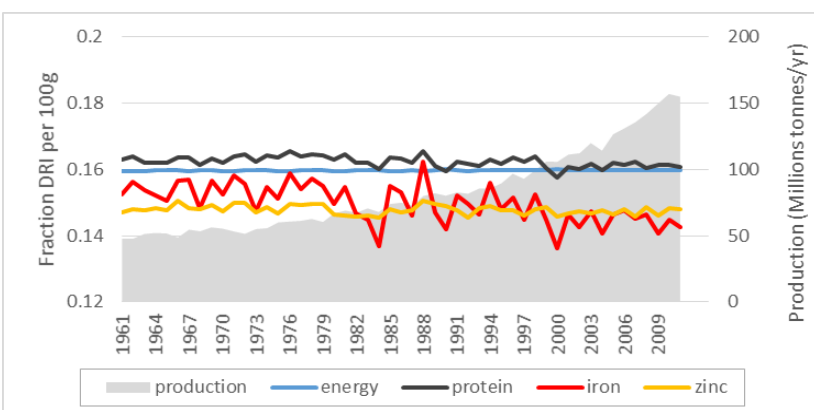
0.2
0.18
0.16
0.14
0.12
0.1
0.08
Fraction DRI per 100g
300
250
200
150
100
50
0
Production (Millions tonnes/yr)
1961
1964
1967
1970
1973
1976
1979
1982
1985
1988
1991
1994
1997
2000
2003
2006
2009
production
energy
protein
iron
zinc


b)



0.2
0.18
0.16
0.14
0.12
0.1
0.08
Fraction DRI per 100g
300
250
200
150
100
50
0
Production (Millions tonnes/yr)
1961
1964
1967
1970
1973
1976
1979
1982
1985
1988
1991
1994
1997
2000
2003
2006
2009
production
energy
protein
iron
zinc


c)

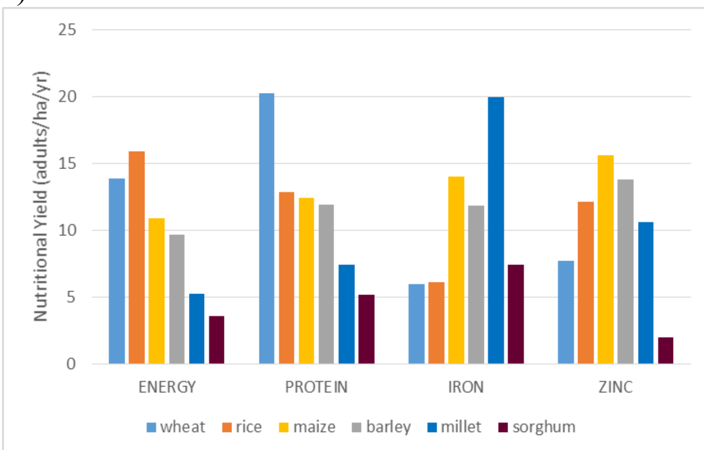


0.2
0.18
0.16
0.14
0.12
Fraction DRI per 100g
200
150
100
50
0
Production (Millions tonnes/yr)
1961
1964
1967
1970
1973
1976
1979
1982
1985
1988
1991
1994
1997
2000
2003
2006
2009
production
energy
protein
iron
zinc

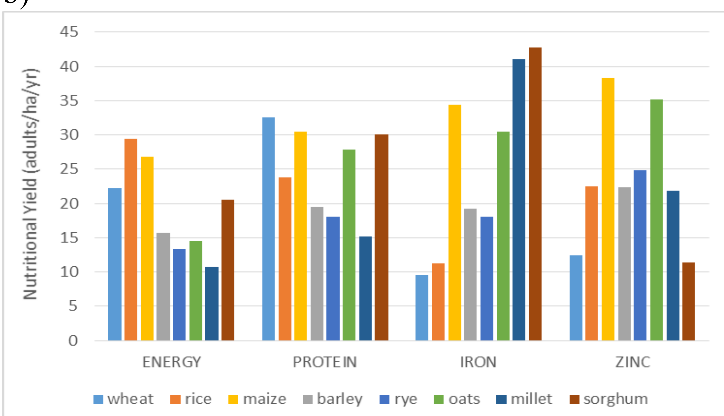
**Fig. S5. Nutritional content as shown in Fig. 1A, but for other areas:** (**a**) India, (**b**) China, and (**c**) Least Developed Countries. Note difference in scale for y-axes. See Fig. S5a, S5b, and S5c Excel spreadsheets for details.

**Fig. S6**

a)




b)




c)

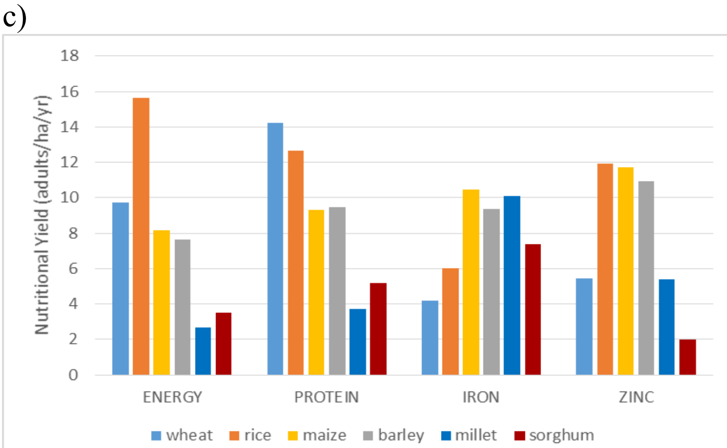



**Fig. S6. Nutritional yields in 2013 as shown in Fig. 1B but for other areas.** (**a**) India, (**b**) China, and (**c**) Least Developed Countries. Note difference in scale for (b). Oats and rye are not included for India and LDCs due to limited production. See Fig. S6 Excel spreadsheet for details.

**Table S1. Sensitivities of nutritional content (fraction DRI/100 g) to changes in mixes of cereal types and diversion to feed.** Values are for each year from 1961 to 2011 and show the average difference between actual nutritional content (fraction DRI/100 g shown in Figs. 1A, S5a, S5b, and S5c for world, India, China, and LDCs, respectively) and hypothetical nutritional content. Diversion to feed is based on the hypothetical nutritional content with no diversion to feed. Change in diversion to feed is based on the hypothetical nutritional content with constant 1961 ratio of food/feed. Change in mix of cereals is based on the hypothetical nutritional content with constant 1961 mix of cereal types. See Table S1 Excel spreadsheet for details.

GLOBAL

| | **Energy** | **Protein** | **Iron** | **Zinc** |
|---|---|---|---|---|
| Diversion to feed | 0.000 | -0.008 | -0.039 | -0.036 |
| Change in diversion to feed | 0.000 | -0.002 | -0.002 | -0.001 |
| Change in mix of cereals | 0.000 | -0.004 | -0.017 | -0.008 |

INDIA

| | **Energy** | **Protein** | **Iron** | **Zinc** |
|---|---|---|---|---|
| Diversion to feed | 0.000 | 0.000 | -0.001 | -0.001 |
| Change in diversion to feed | 0.000 | 0.000 | -0.001 | -0.001 |
| Change in mix of cereals | 0.000 | 0.007 | -0.023 | -0.011 |

CHINA

| | **Energy** | **Protein** | **Iron** | **Zinc** |
|---|---|---|---|---|
| Diversion to feed | 0.000 | -0.003 | -0.028 | -0.025 |
| Change in diversion to feed | 0.000 | -0.001 | -0.004 | -0.001 |
| Change in mix of cereals | 0.001 | 0.000 | -0.049 | -0.020 |

LEAST DEVELOPED COUNTRIES

| | **Energy** | **Protein** | **Iron** | **Zinc** |
|---|---|---|---|---|
| Diversion to feed | 0.000 | 0.001 | 0.001 | -0.001 |
| Change in diversion to feed | 0.000 | 0.001 | 0.003 | 0.001 |
| Change in mix of cereals | 0.000 | -0.001 | -0.003 | 0.001 |

## SUPPLEMENTARY REFERENCES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