The Role of Quantitative Land Evaluation in Food Security Decision Making in China – The Past, Present and Future*

by

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Keywords. — Soil productivity; Climate change; Scenario analysis; Food security; China.

Summary. — China is the most populous country and the second largest economy in the world. Although it has made notable achievements in economic development in the past few decades, food security remains a fundamental issue for many poor and remote households. Here we assess the future trends of Chinese food security in 2050 under soil degradation and climate change scenarios using a Web-based Land Evaluation System. Our results predict that the food security index (FSI), or per capita food surplus in percentage terms, would turn from a 18 unit surplus in 2005 to 3–5, 14–18 and 22–32 unit deficits by 2030–2050 if soil degradation be completely controlled, still occurring at the current rate, and occurring at two times the current rate, respectively. Our results also predict that the FSI would drop from 24 in 2010 to -4.5–7.1 and 10.2–20.0 under the Intergovernmental Panel on Climate Change's high and medium emission scenarios, respectively. These results demonstrate that quantitative land evaluation methodologies can be used as an effective means in large-scale food security decision making.

Samenvatting. — *De rol van kwantitatieve landevaluatie bij de voedselzekerheidsbesluitvorming in China – Verleden, heden en toekomst*. – China is het meest bevolkte land en de op één na grootste economie in de wereld. Hoewel het de laatste decennia opmerkelijke vooruitgang boekte in termen van economische ontwikkeling, blijft voedselzekerheid een fundamenteel probleem voor vele arme en geïsoleerde gezinnen. Met dit onderzoek trachten wij, rekening houdend met bodemdegradatie- en klimaatveranderingscenario's, a.h.v. webgebaseerde landevaluatie in te schatten hoe de Chinese voedselzekerheid er in 2050 zal uitzien. Onze resultaten voorspellen dat de voedselzekerheidsindex, of het in procenten uitgedrukte *per capita* voedseloverschot, zal evolueren van een overschot van 18 eenheden in 2005 naar een tekort van 3-5, 14-18 en 22-32 eenheden tegen 2030-2050 indien bodemdegradatie respectievelijk volledig onder controle zou raken, het huidige tempo blijft aanhouden, en tweemaal zo snel evolueert. Onze resultaten voorspellen ook dat de voedselzekerheidsindex zou terugvallen van 24 in 2010 naar -4,5-7,1 en 10,2-20,0 onder respectievelijk het grote- en middelgrote-uitstootscenario van het *Intergovernmental Panel on Climate Change*. Deze resultaten tonen aan dat kwantitatieve landevaluatiemethodologieën een doeltreffende factor kunnen zijn bij de voedselzekerheidsbesluitvorming op grote schaal.

Résumé. — *Le rôle de l'évaluation quantitative du sol dans la prise de décision en Chine en matière de sécurité alimentaire – Passé, présent et avenir*. – La Chine est le pays le plus peuplé et la seconde économie de la planète. Bien qu'elle ait fait des progrès remarquables en termes de développement économique durant les dernières décennies, la sécurité alimentaire reste une préoccupation majeure pour un grand nombre de ménages pauvres et vivant dans les lieux isolés. Dans cette recherche, nous tenterons de montrer comment on peut prédire, au moyen d'un système d'évaluation des sols basé sur le web, comment la sécurité alimentaire pourrait évoluer en Chine d'ici 2050. Différents scénarios de dégradation des sols et de changement climatique ont été testés. Cet index, en 2005, est estimé à 18. Nos résultats prédisent que l'index de sécurité alimentaire (ISA), ou l'excédent alimentaire par habitant exprimé en pourcentage, changerait d'un surplus de 18 unités en 2005 vers un déficit de 3-5, 14-18 et 22-32 unités en 2030-2050 selon que la dégradation des sols serait entièrement sous contrôle, évoluerait au même rythme qu'actuellement ou deux fois plus rapidement. Nos résultats prédisent également que l'ISA chuterait de 24 en 2010 à 10,2-20,0 ou -4,5-7,1 en tenant compte des scénarios d'émission moyen ou élevé de l'*Intergovernmental Panel on Climate Change*. Ces résultats démontrent que les méthodes quantitatives d'évaluation des sols peuvent être utilisées pour la prise de décision à grande échelle en matière de sécurité alimentaire.

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1. The Global Food Security Challenge

It has been one of the long-standing challenges to sustain a stable supply of food for humanity on Earth. The world population increased more than 260% during the twentieth century, from 1.65 billion in 1900 to over 6 billion in 2000, and is expected to further increase from 7 billion in 2011 to 9 billion in 2050 (SMITH 2011). Overall, food production per capita has remained stable during the twentieth century, largely due to technological advances. Breakthroughs in wheat and rice production, which have been known as the Green Revolution (EVENSON & GOLLIN 2003), have greatly contributed to the ease of the population burden in various parts of the world. The world average yield of cereals leaped from 1.2 t ha^{-1} in 1961 to 3.2 t ha^{-1} in 2010 (ALEXANDRATOS & BRUINSMA 2012), resulting in a substantially higher growth rate in world cereal production (178.4%) than in world population (122.6%) during the past 50 years (Table 1). However, the total harvest area of crops only expanded by a small margin of 7% during 1961-2010, showing the overwhelming importance of yield improvements on maintaining the global food security (YE *et al*. 2013b).

Despite this remarkable progress, 805 million people – one in nine of the world's population – still experience chronic hunger at present (FAO 2014). The vast majority of the hungry people live in the developing world. Globally, some 30 developing countries are classified by the FAO (2014) as having moderately high to very high levels of food insecurity, suggesting that sufficiently accelerated efforts are still urgently needed to fulfill the Millennium Development Goal of halving the proportion of undernourished people worldwide by 2015 (SANCHEZ & SWAMINATHEN 2005).

Continued intensification in food production during the past few decades had notable ecological and environmental consequences. On the one hand, agricultural intensification resulted in, among other benefits, reduced conversion of natural vegetation into crop production (PHELPS *et al.* 2013; XIA *et al.* 2016); but on the other hand, high-intensity production was, among other damages, degrading the soil's ability to build resilience (YE & VAN RANST 2009) and to provide ecosystem services (SQUIRE *et al.* 2015). It is well understood that fertilization played an increasingly important role in intensive production systems. Results of 5334 field trials in China, for instance, indicated that 47.8% of the increase of the yield of major cereal crops was attributed to the use of mineral fertilizers in 1980-1983 (JIN 2012). In 2010, China consumed 49.9 million tons of mineral fertilizers, accounting for 29% of the world's total consumption (Table 1). The use of nitrogen fertilizers (N) in China, in particular, soared from 7 million tons in 1980 to 28 million tons in 2008, but the nitrogen use efficiency declined dramatically by 53% during the same period, from 34 kg grain per kg of N in 1980 to 16 kg grain per kg of N in 2008 (GUO *et al.* 2010). Systematic assessment based on nationwide surveys, pared comparisons and field monitoring datasets revealed that long-term N fertilization at excessive levels in China had caused soil pH to decline significantly from the 1980s to the 2000s in major crop production areas in China (GUO *et al.* 2010).

Table 1

Population, cereal production of the world and of China during 1961-2010

Parameter	1961	1970	1980	1990	2000	2010	1961-2010 Change (%)
- World -							
Population (billion)	3.1	3.7	4.4	5.3	6.1	6.9	122.6
Yield (t ha^{-1})	1.2	1.6	2.0	2.5	2.8	3.2	166.7
Harvest area (million ha)	648.1	708.2	717.3	675.5	648.1	693.2	7.0
Cereal production (million t)	805.2	1087.3	1418	1779.8	1860.7	2241.9	178.4
Fertilizer consumption (million t)	31.6	68.4	116.2	137.0	137.0	172.6	446.2
- China -							
Population (billion)	0.7	0.8	1.0	1.2	1.3	1.4	100.0
Yield (t ha^{-1})	1.0	1.7	2.4	3.6	4.0	4.8	380.0
Harvest area (million ha)	89.7	92.9	94.4	93	85.3	89.9	0.2
Cereal production (million t)	89.1	161	230.6	338.9	342.7	431.1	383.8
Fertilizer consumption (million t)	1.0	3.9	15.3	26.8	34.7	49.9	489.0

Source: IFADATA (http://www.fertilizer.org/Statistics) for fertilizer consumption; FAOSTAT (http://faostat.fao.org) for the others

The demand for food will probably grow by 50% until 2030 and even higher production will have to be achieved through agricultural intensification for a world of 9 billion people in 2050 (TILMAN *et al.* 2002; SCHMIDHUBER & TUBIELLO 2007; YE *et al.* 2016). Given the increasing magnitude of pressures from intensive production systems on ecosystems and the environment (YAO *et al.* 2015), action is needed now to institutionalize and implement sustainable intensification schemes to ensure global food security for decades to come (GODFRAY & GARNETT 2014). Quantitative land evaluation is one of the first technologies to be used for plausible assessments of soil fertility and attainable yield potentials in time and space (YE *et al.* 2008a, 2013b), which in turn form the foundation of more sustainable intensification practices.

2. A Historical Overview of Quantitative Land Evaluation Methodologies

In response to worldwide concerns on the capacity of planet Earth to feed its growing population while ensuring the conservation of its natural resources and the protection of the environment, an internationally accepted approach was elaborated in mid-twentieth century to assess the potentialities as well as the limits of the world's land resources for development (FAO 2007). In October 1972, the methodological framework resulting from this FAO-coordinated international elaboration was presented for the first time at an expert consultation meeting in Wageningen, the Netherlands, where the concepts, principles and procedures of the methodology were extensively discussed and further refined. It was eventually published under the title "A Framework for Land Evaluation" in FAO Soils Bulletin 32 (FAO 1976).

The primary objective of the Framework was the improved and sustainable management of land for the benefit of the people. Although the framework and its largely *qualitative* methodologies remain valid, the emphasis on the *quantitative* assessment of ecosystem services (e.g. food production) and environmental consequences (e.g. impact of climate change) in space and time has been growing since the publication of the Framework (VAN RANST 1996).

The quantitative land evaluation methodologies presented in this paper adopt a three-step, hierarchical, deterministic crop growth model (YE & VAN RANST 2002, 2009, YE *et al.* 2008a) based on the radiation regime (FAO 1984, SYS *et al*. 1991b) and the limiting and reducing factors (VAN RANST & VANMECHELEN 1995, TANG *et al.* 1992; VERDOODT *et al.* 2004) on the growth of specific crops.

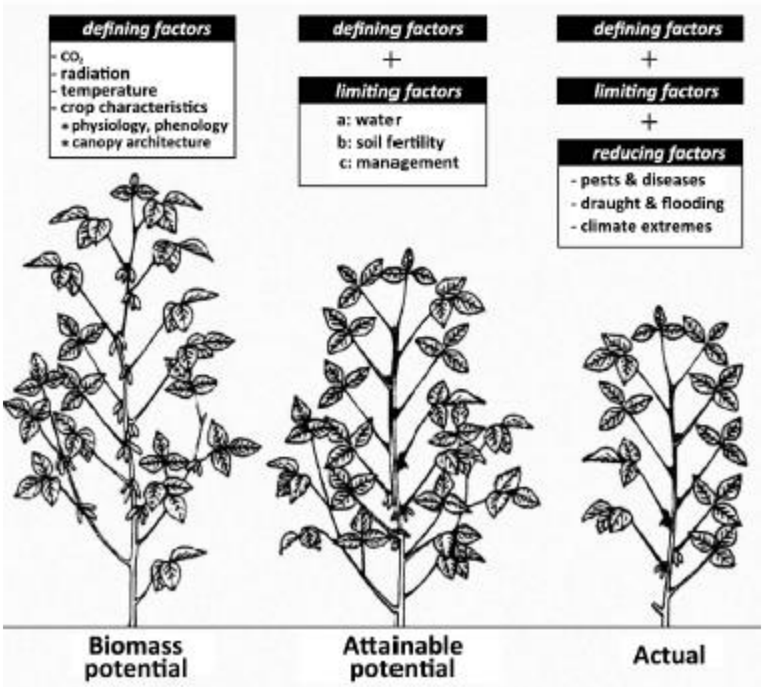

Fig. 1. — The conceptual structure of a hierarchical crop growth model involving the assessments of the biomass potential, attainable potential and actual crop yield (modified from VAN ITTERSUM 2003).

2.1. Crop yield modeling

The area-weighted average crop yield Y (t ha^{-1}) is calculated from the average rainfed (Y_{rain}) and irrigated (Y_{irri}) yields (YE *et al.* 2008a):

$$Y = \sum_{i=1}^{N} \left(\frac{A_{irri} \cdot Y_{irri} + A_{rain} \cdot Y_{rain}}{A_{irri} + A_{rain}} \right)_i \quad (1)$$

where i is the serial number of a rotating crop, i = 1...N; and A_{irri} and A_{rain} are the areas (ha) of the irrigated and rainfed croplands, respectively. The ratio $A_{irri}/(A_{irri}+A_{rain})$ represents the likelihood that a particular tract of cropland is irrigated. Y_{irri} and Y_{rain} are given by the following formulas (SYS *et al*. 1991a, 1991b, TANG *et al.* 1992):

$$Y_{rain} = B_n \cdot HI \cdot f_w \cdot S_y \cdot M_y \cdot E_y \quad (2)$$

$$Y_{irri} = B_n \cdot HI \cdot S_y \cdot M_y \cdot E_y \quad (3)$$

where B_n is the net biomass production (t ha^{-1}); HI is the harvest index; f_w is the yield reducing coefficient due to water stress (dimensionless); S_y and M_y are the soil and management indices (dimensionless), accounting for the yield effects of soil and management limitation, respectively; and E_y is the environmental index or the aggregate yield effect of environmental stressors.

The net biomass (B_n) accumulated during the crop cycle is calculated by:

$$B_n = \frac{0.36 \cdot bgm \cdot (0.35LAI - 0.03LAI^2)}{L^{-1} + 0.25 \cdot c30 \cdot (0.044 + 0.0019t + 0.001t^2)} \quad (4)$$

where bgm is the maximum gross biomass production rate (t CH_2O ha^{-1} day^{-1}), which is constrained by the radiation regime (i.e., the photosynthetically active radiation) and the crop genotype (i.e., the maximum leaf photosynthesis rate); LAI is the actual maximum leaf area index (m^2 m^{-2}); L is the length (days) of the crop cycle; $c30$ = 0.00283 for legumes and 0.00108 for non-legumes; and t is the mean daily temperature (ºC). A concise derivation of Eq. 4 can be found in YE & VAN RANST (2002). It has been applied in the assessment of crop production in Mozambique (KASSAM *et al.* 1982) and in calculations of the population supporting capacities of the developing world (HIGGINS *et al.* 1982) and, in particular, China at the national (SLA 1994) and county (YE & VAN RANST 2002) scales.

The yield reducing coefficient (f_w) represents the aggregate effect of water stress on crop yield and can be evaluated from the relative evapotranspiration deficit and the yield response factor (k_y):

$$f_W = \sum_{i=1}^{M} \left\{ \frac{L_i}{L} \left[1 - k_{y(i)} \left(1 - \frac{ET_{a(i)}}{ET_{m(i)}} \right) \right] \right\} \quad (5)$$

where i is the serial number of a crop growth period (CGP, including establishment, vegetative growth, flowering, yield formation and ripening), i = 1..M; L_i is the length (days) of the i^{th} CGP; L is the length (days) of the crop cycle, $L = \sum L_i$; and $ET_{a(i)}$ and $ET_{m(i)}$ are the actual and maximum crop evapotranspiration (mm) in the i^{th} CGP, respectively. The yield response factor, $k_{y(i)}$, measures the yield effect of water stress in the i^{th} CGP. CGP-specific values of k_y can be found from published tables (e.g. SYS *et al.* 1991a). The value of ET_m is obtained by combining the reference evapotranspiration (ET_o) and the crop coefficient (K_c) (ALLEN *et al.* 1998):

$$ET_m = K_c \cdot ET_o \tag{6}$$

where ET_o is estimated from climatic parameters following the modified Penman-Monteith approach (SMITH 1991). The actual evapotranspiration (ET_a) is the amount of water that is actually removed from the soil due to the processes of evaporation and transpiration. The ET_a accumulated over a period of t days after a fraction (f) of the available soil moisture (S_a) over a rooting depth (D) has been depleted is given by the following equation (DEBAVEYE 1986):

$$ET_a = \left\{1 - \exp\left[-\frac{ET_m \cdot t}{(1-f)\cdot S_a D}\right]\right\} \cdot S_t D \tag{7}$$

where $S_t D$ is the available soil water storage at time t over a rooting depth D.

The soil and management indices account for the adverse effects of limited soil fertility and poor crop management on yields, respectively. The soil index is obtained by combining the rating values of all of the limiting soil parameters (YE *et al.* 2008a, YAO *et al.* 2015) by using the STORIE (1976) method:

$$S_y = \prod_i \left(\frac{R_i}{100}\right) \tag{8}$$

where R_i is the rating value (range: 0-100) of the i^{th} limiting soil parameter (SYS *et al.* 1993). The management index is evaluated from the overall scores derived from the management parameters:

$$M_y = \left(\frac{S_i}{\max(S_i)}\right)^b \tag{9}$$

$$S_i = \sum_j \frac{I_{ij}}{\min(I_j)} \tag{10}$$

where S_i is the overall score obtained from crop management parameters in province i; I_{ij} is the value of management parameter j in province i; I_j is the data series of management parameter j in all provinces; and b is a crop-specific coefficient determined by a single-factor Cobb-Douglas production function ($Y_o = a \cdot S^b$) fitted between the observed yield Y_o and the overall score S (YE & VAN RANST 2009).

The environmental index E_y accounts for the impact of environmental stressors on yields. It has been a challenging task to quantitatively assess the effect of one or more environmental stressors on yield. Two ad-hoc approaches are used as examples to deal with stressors such as soil degradation (BINDRABAN *et al.* 2012) and climate change (YE *et al.* 2013b, 2014); details of such approaches are discussed in sections 3.2 and 3.3, respectively. For simplicity, the interactions between climate change and soil degradation are not considered in this paper.

2.2. Recent methodological advances

Major methodological advances in quantitative land evaluation since the 1990s include:

- Application of fuzzy set theory in the assessment of soil limitations on crop yield, as pioneered by the research team of the Laboratory of Soil Science at Ghent University in the 1990s (TANG *et al.* 1991, TANG & VAN RANST 1992, VAN RANST *et al.* 1996, TANG *et al.* 1997, GROENEMANS *et al.* 1997a, 1997b, VAN RANST & TANG 1999);
- Inclusion of oxygen availability into soil water balance simulation to improve the accuracy of the assessment of the effect of water stress on crop yield (VERDOODT *et al*. 2005);
- Development of a Web-based Land Evaluation System (WLES, http://weble.ugent.be) to facilitate large-scale grid simulation of crop yield (YE et al., 2008b) and to function as a building block in, e.g., food security assessments (BINDRABAN *et al.* 2012, YE *et al.* 2013b);
- Application of Cobb-Douglas Production Functions in the assessment of the effect of management levels and practices on crop yield (YE & VAN RANST 2009) and in the identification of the impact of production intensification on soil quality (YAO *et al.* 2015).

3. Food Security Assessments in China

3.1. The assessment framework

To facilitate large-scale grid simulation (YE *et al.* 2008b) of the effect of environmental change on long-term food security in China, a five-step approach was developed by YE & VAN RANST (2009). First, climatic, crop, soil, management and socio-economic data were collected, manipulated and used to simulate the yields of food crops using WLES. Second, the simulated yields were compared to the observed yields in order to validate the simulation process. Third, the food production capacities in 2030 and 2050 were estimated based on the most likely scenarios of population growth, urbanization rate, cropland area, cropping intensity and the environmental stressor in concern. Fourth, a food security index (FSI) was computed following an equilibrium analysis of the supply-demand relationship for food produced from agricultural crops. Finally, the effect of the environmental stressor on the FSI was quantitatively evaluated.

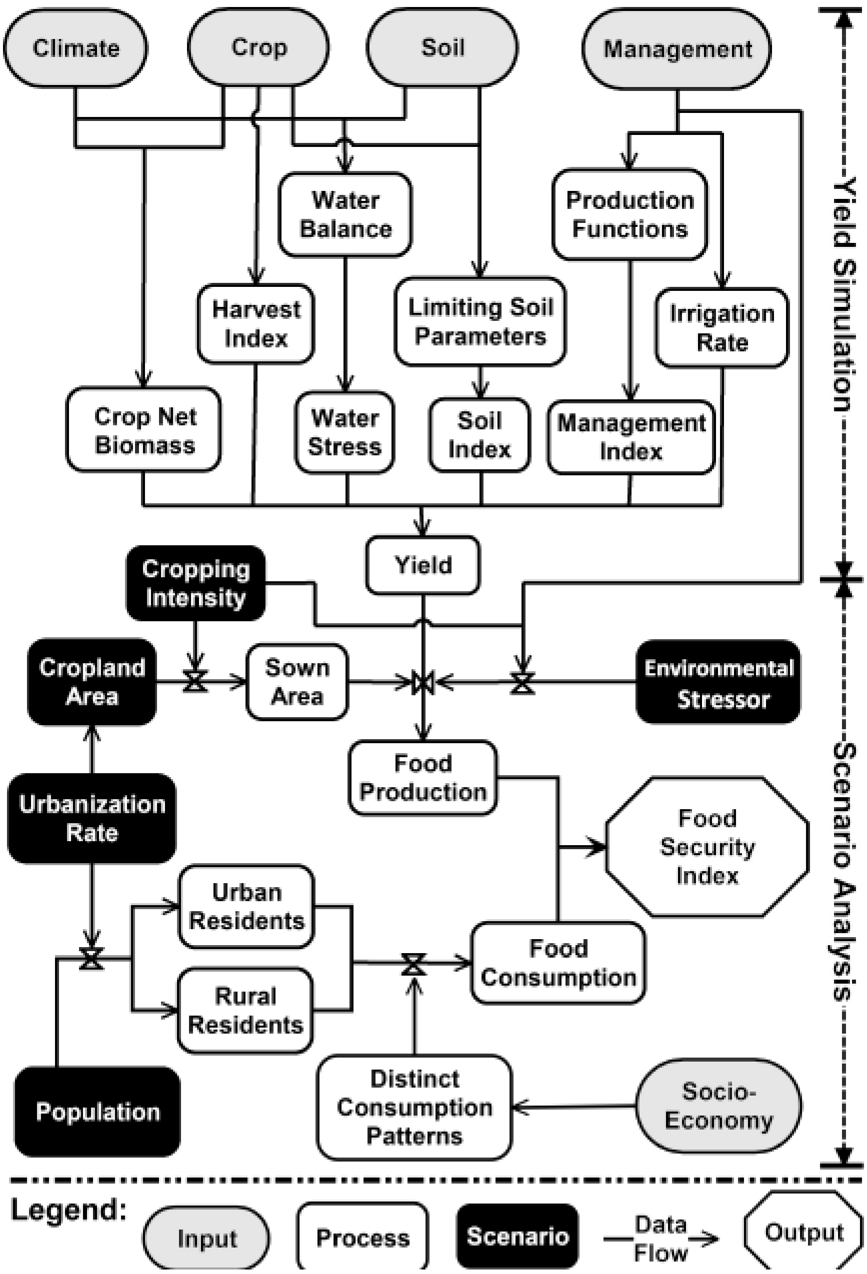

Fig. 2. — The flowchart of the food security assessment framework.

3.2. Impact of soil degradation

Soil degradation is a strong environmental stressor (BINDRABAN *et al.* 2012), which can be considered as a yield-reducing factor in quantitative land evaluation (Fig. 1). Its effect on crop yield is evaluated using the following equation:

$$Y_2 = \left(1 - n \cdot \frac{t_2 - t_1}{15} \cdot \frac{p}{100}\right) \cdot Y_1 \quad (11)$$

where p is the relative yield penalty (%) due to soil degradation during a 15-year period prior to year t_1, Y_1 is the average yield observed in year t_1, Y_2 is the average yield in year t_2, n is a multiplicative coefficient representing the severity of soil degradation (see the next paragraph for further details).

The relative yield penalty (%) due to soil degradation, *p*, was estimated for China (Table 2) using the qualitative soil degradation classes of ISRIC's ASSOD map which followed the GLASOD approach (VAN LYNDEN & OLDEMAN 1997). The resulting average yield penalties in eastern, middle and western China were 1, 4 and 25%, respectively, under the 2005 level of crop management, meaning that crop yield would be 1, 4 and 25% higher than the current obtained yield should soil degradation not have occurred. The relative yield penalty at the national scale was estimated at 9%, which is consistent with earlier reports (ROZELLE *et al.* 1997).

Table 2

Relative yield penalty (%) for five classes of soil degradation and three levels of agronomic management

Degradation	**High input**	**Intermediate input**	**Low input**
Negligible	0	0	10
Light	0	10	25
Moderate	10	25	50
Strong	25	50	75
Extreme	50	75	100

Three soil degradation scenarios were designed. Under the business-as-usual scenario (BAU), soil degradation occurred at the current intensity. The same amount of yield would be lost in the next 15 years as in the past 15 years, or n (Eq. 11) = 1. Under the zero-degradation scenario (0×SD), no degradation would occur (n = 0), whereas under the double-degradation scenario (2×SD), soil degradation would occur at twice the rate, limiting the crop yield more than at present (n = 2). A summary of all scenario settings is given in Table 3.

Table 3

Settings of the parameters involved in scenario analysis for food security assessment

Scenario	**2005**	**2030**	**2050**
Population (billion)	1.31	1.46	1.44
Urbanization (%)	42.99	72.56	82.56
Cropland (million ha)	130	113	107
Multi-cropping index (%)	120	133	147
Soil degradation (yield loss since 2005)			
Zero degradation	-	$0\times p$ [a]	$0\times p$
Business-as-usual	-	$1.67\times p$	$3\times p$
Double degradation	-	$3.33\times p$	$6\times p$

[a] *p*: relative yield penalty (%) between 1990 and 2005 (see Eq. 11).

The relative food surplus was defined as the food security index, or FSI, in an attempt to measure the general status of food security in China:

$$FSI = \frac{s \cdot g^{-1} - d}{d} \cdot 100 \tag{12}$$

where *s* is the per capita food supply (kg), *d* is the per capita food demand (kg), and *g* is the expected food self-sufficiency level. The Government goal is to maintain a self-sufficiency level of 95% ($g = 0.95$), allowing the remaining 5% of food demand to be met by imports (YE *et al.* 2016). The per capita demand *d* is evaluated based on consumption patterns of the urban and rural populations, respectively (YE & VAN RANST 2009), while the per capita supply is given by:

$$s = 1000 \cdot \left[\sum_{i=1}^{n} \left(Y_i \cdot A_i \right) \right] \cdot P^{-1} \tag{13}$$

where *i* stands for a crop, *n* is the total number of food crops, *Y* is crop yield (t ha^{-1}, Table 4), *A* is crop area (ha, Table 3) and *P* is the population size (persons, Table 3).

The curve of FSI, based on the census and estimated data for the pre-2005 period and on scenarios for the post-2005 period, are given in Fig. 3a. Historical variations in food security are well captured by FSI. China's food security status was significantly improved soon after the long-lasting wars that ended in the late 1940s. At the end of the first five-year plan, the FSI increased from -0.4 in 1949 to 32.7 in 1957, showing that the supply-demand equilibrium turned from a 0.4% deficit to a 32.7% surplus. The peak FSI value of 38.5 appeared in 1984, coinciding with the record harvest of 390 million tons in the same year. Although higher productions (~500 million tons) were achieved consecutively during 1996-1999, the FSI values in the same period were not higher than that of 1984, reflecting the combined effects of a larger population and a higher standard of living. Extreme climatic events and natural hazards, which caused notable production losses during 2000-2003, were responsible for the second largest drop in the FSI values after the period of the Great Leap Forward (1957-1961).

China faces great environmental challenges in safeguarding its food security in the long run. The FSI is predicted to drop from 18 in 2005 to -5 and -3 in 2030 and 2050, respectively, under the 0× SD scenario (Fig. 3a), exhibiting the adverse effect of population growth on food security. This, together with the finding that the positive effect of agricultural intensification cancels the negative effect of the loss of cropland, suggests that the present-day (2005 level) production capacity will not sustain the long-term needs of the Chinese population, even under the 0× SD scenario. Results also show that 14-18% and 22-32% of per capita demands will not be met by 2030-2050 under the BAU and 2× SD scenarios, respectively (Fig. 3a). This translates into a total increase of 300-500 million malnourished people in 2050, in addition to the 2005 level of 120 million.

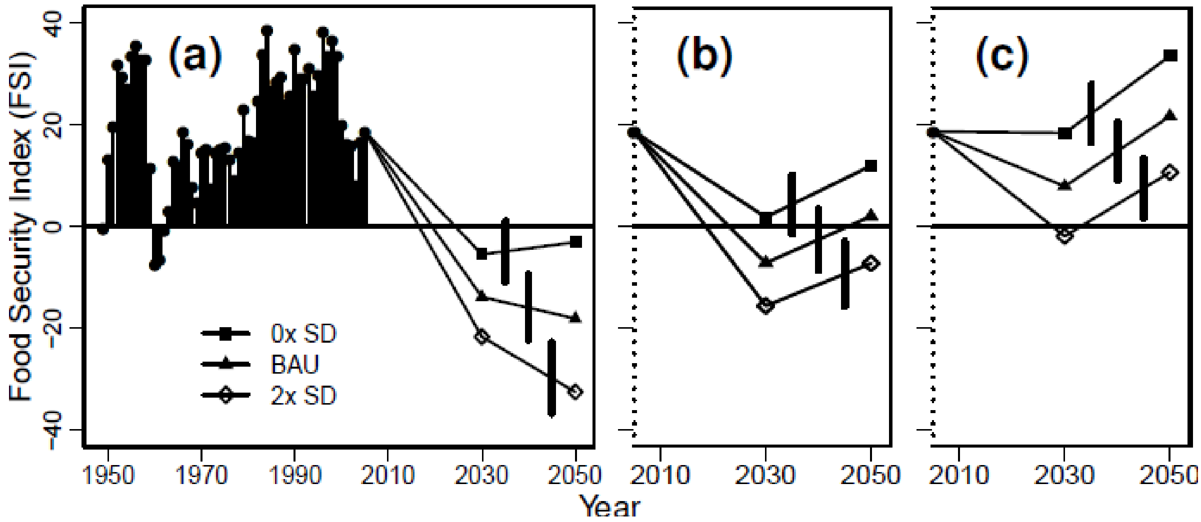

Fig. 3. — Historical fluctuations and future trends of food security index (FSI) in China. (a) FSI under the zero degradation (0x SD), business-as-usual (BAU) and double degradation (2x SD) scenarios in 2030-2050 as compared to the period 1949-2005. The solid horizontal line (FSI = 0) represents the 95% food self-sufficiency level. (b) FSI in 2030 and 2050 under the raised management scenario. (c) FSI in 2030 and 2050 under the scenario of science and technology breakthroughs in crop breeding. (a-c) A thick vertical bar depicts the standard deviation of the FSI under a degradation scenario.

These alarming impacts of soil degradation on food security suggest that policy interventions are needed now to mitigate or even to prevent the adverse effects of soil degradation on food production in the future. Two additional policy scenarios are designed for this purpose. One is the raised management scenario and the other is the higher-yielding varieties scenario. Under the raised management scenario (Fig. 3b), crop management level in middle China is raised to the same level as in eastern China; crop management level in western China is raised to the level of middle China in 2030 and to the level of eastern China in 2050. Under the higher-yielding varieties scenario (Fig. 3c), yields are steadily improved at an average rate of 0.8% yr^{-1} during 2005-2030 and 0.5% yr^{-1} during 2030-2050 by gradually adopting higher-yielding varieties (ZHAO *et al.* 2008). The model predicts significantly positive responses of the FSI values under all degradation rates to either the higher management scenario (Fig. 3b) or the higher-yielding varieties scenario (Fig. 3c). The rice hybrids, for instance, that are planted in more than half of the total rice-growing area in China have achieved a stable yield advantage of at least 15% over the best inbred varieties (YUAN 2001). The extension of hybrid rice breeding in China serves as a good example that demonstrates how investment and effective policies are rewarded by improved food security.

3.3. Impact of climate change

The quantitative land evaluation model was also employed to simulate the effect of climate change on crop yield and to predict future trends of food security in China under climate change scenarios. The historical climate during 1961-1990 was used as a baseline with the CO_2

concentration set at ~330 ppm. The SRES A2 and B2 scenarios were selected to represent two contrasting GHG emission as well as development pathways, pessimistic versus optimistic, for China, respectively. The IPCC SRES A2 scenario describes a very heterogeneous world of high population growth, slow economic development and strong regional cultural identities, while the B2 scenario reflects a heterogeneous world with diverse technological change, low population growth and emphasis on local solutions to economic, social and environmental sustainability problems.

Crop yield was simulated per grid cell of 10 km using the WLES model (YE *et al.* 2008b). The aggregated results at the national scale and averaged at the decadal time scale are given in Table 4. The results show that climate change is simulated to have moderately positive effects on the yields of rice, wheat and maize in China at the decadal time scale from 2020 through 2050 (Table 4, no technology). The maize yield, for instance, is projected to increase by ~10%, from 5.3 t ha^{-1} in 2009 to 5.8 t ha^{-1} in 2050, under the A2 scenario. Under the B2 scenario, a 4% increase in maize yield is projected. Overall, crop yields are projected to increase in 21 out of 24 cases (3 crops by 4 decadal intervals by 2 scenarios, Table 4, no technology). The wheat yield is projected to be mostly stagnated or decrease by a small margin under either A2 or B2. The average yield of all cereals taken together is projected to increase by 11% from 4.9 t ha^{-1} in 2009 to 5.4 t ha^{-1} in 2050 under A2, assuming that the sown area proportions of individual crops in 2009 are kept unchanged during the entire projection period, while this yield increase is projected to be 4% under B2, meaning that short-to-medium-term yield growth is more likely to be achieved under the A2 scenario which assumes higher emission levels (320% more CO_2 in 2100 than in 2000), as also observed by others (e.g., PARRY *et al.* 2005). Agricultural production will likely benefit from a more balanced development pathway as assumed under B2, but this benefit may probably only be achieved over longer terms.

Table 4

Yield of major cereal crop in China under the considered socio-economic and agronomic scenarios in association with the SRES A2 and B2 emission scenarios. Numbers inside parenthesis are percent increase against the baseline values

Year	**No technology development**			**Technology development**		
	Rice (t ha^{-1})	**Wheat (t ha^{-1})**	**Maize (t ha^{-1})**	**Rice (t ha^{-1})**	**Wheat (t ha^{-1})**	**Maize (t ha^{-1})**
- Baseline -						
2009	6.6	4.7	5.3	6.6	4.7	5.3
- SRES A2 -						
2020	7.0 (6)	4.7 (0)	5.4 (2)	7.3 (11)	4.9 (4)	5.6 (6)
2030	7.2 (9)	4.8 (2)	5.5 (4)	7.5 (14)	4.9 (4)	5.8 (9)
2040	7.5 (14)	5.0 (6)	5.7 (8)	7.7 (17)	5.1 (9)	5.8 (9)
2050	7.8 (18)	5.3 (13)	5.8 (9)	8.0 (21)	5.4 (15)	6.0 (13)
- SRES B2 -						
2020	7.2 (9)	4.7 (0)	5.5 (4)	7.7 (17)	5.1 (9)	5.9 (11)
2030	7.3 (11)	4.7 (0)	5.6 (6)	7.9 (20)	5.1 (9)	6.1 (15)
2040	7.2 (9)	4.9 (4)	5.6 (6)	7.5 (14)	5.2 (11)	5.8 (9)

2050	7.1 (8)	5.1 (9)	5.5 (4)	7.4 (12)	5.4 (15)	5.8 (9)

This large positive effect of climate change on crop yield contrasts with many earlier estimates. One fundamental difference between this research and the earlier estimates is that CO_2 fertilization (GOSLING *et al.* 2011, LOBELL & FIELD 2008) was intentionally included in this simulation, while CO_2 fertilization was excluded from others such as PARRY et al. (2004). The rationale to consider CO_2 fertilization is that the rise of atmospheric CO_2 concentration has already been an observed fact and it will continue to rise in the foreseeable future, despite uncertainties about the magnitude of this rise (LIN *et al.* 2005, LONG *et al.* 2006). Along with temperature warming (YE *et al.* 2013a, 2013b, 2014), elevated CO_2 concentrations stimulate photosynthesis, by a margin of ~0.08% for rice and wheat and ~0.05% for maize per 1 ppm increase, leading to increased plant productivity and modified water and nutrient cycles. Past studies suggested that crop yield tends to increase under higher CO_2 concentrations (TUBIELLO *et al.* 2007). Compared with the current atmospheric CO_2 concentrations of ~380 ppm, crop yields increase at 550 ppm CO_2 in the range of 10-20% for C_3 crops (e.g., rice and wheat) and 0-10% for C_4 crops (e.g., maize). The magnitude of the positive yield effects found here (Table 4, no technology) fell well within this range. Although the robustness of CO_2 fertilization is being debated (GOSLING *et al.* 2011; LONG 2012), its yield effect has been confirmed by a variety of field experiments such as the free-air carbon dioxide enrichment (FACE) experiment.

Future trends of food security in terms of the FSI in China under climate change scenarios A2 and B2 are shown in Fig. 4. The FSI is predicted to drop sharply from 24.2 in 2009 to 10.2 and -4.5 in 2030 under the B2 and A2 scenarios, respectively. During the period of 2030-2050, the FSI is predicted to increase from -4.5 in 2030 to 7.1 in 2050 under the A2 and from 10.2 to 20.0 under the B2 scenario (Fig. 4), reaffirming the controlling effect of population growth on food security in populous countries like China. Therefore, as a countermeasure for food security, the yield growth rate should be maintained at a level higher than that of population growth (HOPFENBERG & PIMENTEL 2001) Alternatively, population control should be prioritized where proper yield growth rate cannot be sustained (EHRLICH & EHRLICH 2009).

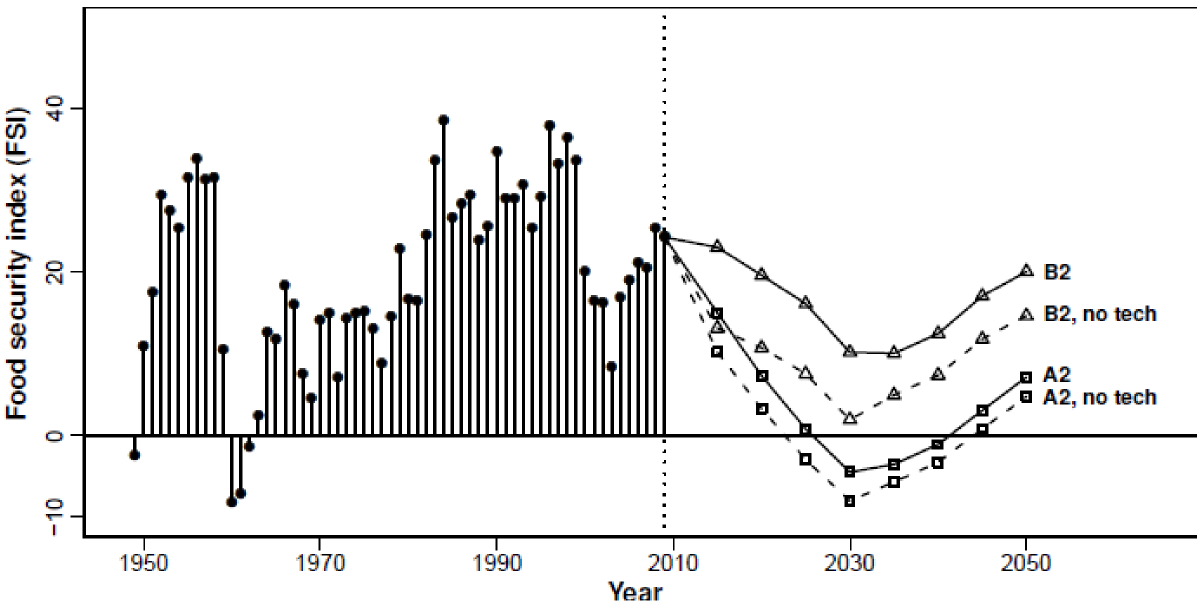

Fig. 4. — Food security index (FSI), as evaluated using census data during 1949-2009 and as projected in 2030 and 2050 under two contrasting emission scenarios, SRES-A2 and -B2. Horizontal bars represent the average FSI levels at the decadal time scale.

A comparison between the simulated FSI curves under the A2 and B2 associated scenarios shows that the socio-economic and agronomic pathways in association with the A2 and B2 emission scenarios have significant impact on FSI. The average distance between these two curves during 2011-2050 is evaluated to be 13 units, meaning that food surplus linked with a more balanced development pathway (B2, low population growth, stimulation of technological change and emphasis on environmental sustainability) is 13% higher than a more stagnated pathway (A2, high population growth, low economic development, low regional coordination). This difference can translate into 76 million tons of additional grain harvests in 2030 under B2. The average distance between the simulated FSI curve under B2, for example, and the FSI curve under B2 but excluding technology development during 2011-2050 (Table 4, technology development) is evaluated to be 7 units (Fig. 4). This reveals that yield improvements realized by technology development (Table 4, technology development) alone may have raised the food surplus level during 2011-2050 under B2 by 7%, suggesting that technology development is one critical means to raise food security level through yield growth rate maintenance (ALSTON *et al.* 2009).

4. Conclusions and Recommendations

The most important conclusions are:

- Quantitative land evaluation is an important extension to the Framework methodologies toward effective assessment of ecosystem services and environmental impact on the terrestrial farming systems in space and time;

- The Web-based Land Evaluation System (WLES) greatly facilitates large-scale grid simulation of crop yields. Together with the food security index (FSI), it acts as a promising tool in food security decision making in populous countries like China;
- Environmental degradation and change have enormous impact on Chinese food security. Institutional and policy actions are needed now to mitigate, if not to reverse, further damages on the livelihood and wellbeing of at least one-fifth of the world population.

We advise the following recommendations:

- Continuous effects are needed to integrate the latest science and technology developments into the methodological arena of land evaluation. Big data generated by various Earth observation satellites, for example, is one of the many directions which deserve more attention;
- Agricultural investment in research and in field is itself an effective adaptation/mitigation measure in both cases of soil degradation and climate change. Yield improvements through better management and high-yielding varieties have the potential to reverse the negative effects of environmental change on food security in both cases;
- Progressive policy actions are needed not only to increase agricultural production, but also to boost income and reduce poverty in remote areas where most of the poor live. As such, everyone (not only the rich) has the financial capacity to improve his or her food security status facing environmental change.

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