

The past and future of food stocks

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The past and future of food stocks

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Francesco Laio¹, Luca Ridolfi¹ and Paolo D'Odorico²¹ Department Environmental, Land and Infrastructure Engineering, Politecnico di Torino, C.so Duca degli Abruzzi 24, I-10129, Turin, Italy² Department Environmental Sciences, University of Virginia, Charlottesville, VA 22904, USAE-mail: Francesco.laio@polito.it**Keywords:** food security, grain stock dynamics, food crises, stochastic modeling**Abstract**

Human societies rely on food reserves and the importation of agricultural goods as means to cope with crop failures and associated food shortage. While food trade has been the subject of intensive investigations in recent years, food reserves remain poorly quantified. It is unclear how food stocks are changing and whether they are declining. In this study we use food stock records for 92 products to reconstruct 50 years of aggregated food reserves, expressed in caloric equivalent (kcal), at the regional and global scales. A detailed statistical analysis demonstrates that the overall regional and global per-capita food stocks are stationary, challenging a widespread impression that food reserves are shrinking. We develop a statistically-sound stochastic representation of stock dynamics and take the stock-halving probability as a measure of the natural variability of the process. We find that there is a 20% probability that the global per-capita stocks will be halved by 2050. There are, however, some strong regional differences: Western Europe and the region encompassing North Africa and the Middle East have smaller halving probabilities and smaller per-capita stocks, while North America and Oceania have greater halving probabilities and greater per-capita stocks than the global average. Africa exhibits low per-capita stocks and relatively high probability of stock halving by 2050, which reflects a state of higher food insecurity in this continent.

Introduction

The global demand for agricultural products is dramatically increasing as a result of population growth, dietary changes, economic development, and new bioenergy policies (Godfray *et al* 2010, Tilman *et al* 2011, Cassidy *et al* 2013, Brown 2013). There are major concerns about the ability of the planet to sustainably feed the growing and increasingly affluent human population (Godfray *et al* 2010, Foley *et al* 2011, UN 2011, Kastner *et al* 2012, Davis *et al* 2014). The recent food crises of 2008 and 2011 have shown how the effects of local crop failures can spread worldwide, leading to the emergence of global food insecurity (Fader *et al* 2013, Porkka *et al* 2013, D'Odorico *et al* 2014). These episodes indicate the possible vulnerability of the global food system, likely as a result of the increasing reliance on tightly country-connecting trade, low agriculture diversity, and the loss of redundancy in the balance between food demand and agricultural production (Fraser

et al 2005, D'Odorico *et al* 2010, Suweis *et al* 2013, Puma *et al* 2015). Research on factors such as food stocks and grain reserves that contribute to such a redundancy remains limited and strongly focused on resource economics rather than food security (Liliston and Ranallo 2012).

Global food availability depends on a dynamic balance between supply and demand (Cassidy *et al* 2013, Porkka *et al* 2013, D'Odorico *et al* 2014, Carr *et al* 2015). This balance is complex, unsteady, and precarious (Puma *et al* 2015, Suweis *et al* 2015) because demand is relatively inelastic while supply exhibits high short-term variability due to several anthropogenic (e.g., wars, embargoes, socio-economic crises, climate change, or linkages with energy market) and natural (e.g., droughts, floods, or pests) drivers acting at different temporal and spatial scales (e.g., Calderini and Slafer 1998, Carter *et al* 2011, Ben-Ari and Makowski 2014).

In this context, stocks play a fundamental role in modulating the impacts of fluctuations in crop

production and food price in the international market (Liliston and Ranallo 2012, Gouel 2013), by enhancing the resilience of the food system and reducing its vulnerability (Adger 2006). Food reserves can be used to mitigate the impact of environmental and economic crises (Wiggins and Keats 2009, Simelton 2011), reduce food price volatility and increase food security (Wright 2011, Wright and Cafiero 2011, Cafiero *et al* 2015, Fraser *et al* 2015), cope with humanitarian emergencies, or prevent market failure; but they can also be used for financial speculations (Von Braun 2007). It follows that stock management can be one of the most important levers to control the supply/demand balance—and therefore improve the food system capability to adsorb disturbances, namely to increase resilience—though its real effectiveness depends on a number of other socio-economic factors (World Bank 2012).

The wide spectrum of possible uses of food stocks, their different typologies (from farm to country scale), geographic distribution, and interplay with the food supply–demand system (Von Braun 2007) make the dynamics of global food stocks very complex, with remarkable trends and fluctuations at different spatial and temporal scales. This complexity is also contributed by technical and economic management issues. Despite the crucial role played by stocks on global food security and food markets, their dynamics remain poorly understood and no framework exists for their analysis. Here we approach the problem from a data-based perspective; we investigate trends and fluctuations in food stock records and develop a stochastic model to analyze food stock dynamics and evaluate the likelihood that different regions of the world might see dramatic declines in their food reserves in a foreseeable future.

Materials and methods

Per-capita stock estimation

The analysis of stock data requires some caution because of uncertainties existing in the available data due to a variety of factors, including limitations in stock accounting methods, incomplete or missing records from some countries (particularly in the developing world), the existence of different stock types, the lack of household and warehouse food storage records, and the seasonality of stocks (Bobenrieth *et al* 2012, Abbott 2013, Fraser *et al* 2015). Aware of these issues, we adopt some precautionary measures that allow us to reduce the uncertainty. To that end, (i) we study stock dynamics both at the global scale and for major macro-regions of the World, and not at the scale of the single country; (ii) we evaluate regional stocks using a large number of food items; and (iii) we carefully process the data adopting conservative assumptions and avoiding the introduction of bias when item- and country-specific data are aggregated.

Aggregation both at the food commodity level and at the continental scale (i.e., aggregating all countries in a continent or subcontinent) are especially important to increase the signal-to-noise ratio, because of the mutual compensation of errors arising from the evaluation of stocks of single items within single countries.

Consider a food product P and a country or region i : we call $S_i^P(t)$ the stock (in tons) available in year t . Food stock data from the ‘Food Balance Sheets’ in the FAOSTAT database (FAO 2015) are available as inter-annual variations in the overall food reserves for a total of 92 food products and 253 countries. For specific products and countries, a comparison of food-stock data from different sources (including FAOSTAT) has been performed within the AMIS initiative (AMIS 2015); in the great majority of cases, stock data from different sources overlap, thus supporting the choice of the FAOSTAT database as the reference for our analyses (the same data source was recently used by Fraser *et al* (2015) to investigate the food system resilience).

For each product P and country i , data are reported in terms of year-to-year variation of the stored amount (in tons) for years from 1961 to 2011. Thus, these records provide annual increments in stocks, $\Delta_i^P(t) = S_i^P(t) - S_i^P(t-1)$, while actual stock data need to be reconstructed from such increments. Reconstruction of stocks from their variations may be performed in many different ways, because one can always add a constant value to the stock time series without affecting their annual variations. There is a thus an inherent subjectivity in the reconstruction process. A first approach could assume that stocks were null in the year before the beginning of the time series (year 1960). In this case the stock in year t would be estimated as $\hat{S}_i^P(t) = \sum_{\tau=1961}^t \Delta_i^P(\tau)$. However, this estimator may produce unrealistic results, with stocks becoming negative at some point in the course of the study period. This fact suggests that the stock was not null in 1960. A more realistic estimation is obtained assuming that, rather than becoming negative, the stocks are completely depleted (i.e., they become zero) in the year in which $\hat{S}_i^P(t)$ is minimum. We thus define the minimum stock value as $M_i^P = \min[\hat{S}_i^P(t)]$ and propose a modified estimator $\tilde{S}_i^P(t) = \hat{S}_i^P(t) - M_i^P$, which has the same variability as $\hat{S}_i^P(t)$ but is increased by a constant quantity (note that $M_i^P \leq 0$). With this assumption we are not eliminating the subjectivity, which is intrinsic in the reconstruction of a variable from its variations, but we are not making arbitrary assumptions on the initial stocks.

Because the stocks are sampled at the same time for all products and all countries, they can be added together without any risk of distorting the analysis. In contrast, other stock accounting methods, as for example the so-called ‘ending stocks’ (which refer to

the pre-harvest date) refer to different dates of the year for different products and countries (Sharples and Krutzfeldt 1990), thus complicating multi-product and multi-country aggregations. Moreover, the meaning of ending stocks becomes unclear in a system in which there is not a single time of the year in which stocks may increase because of multicropping practices and international food trade.

To evaluate their impact on food security, stocks are converted from mass to energy units (i.e., from tons to kcal) using conversion factors available from the FAO (see D'Odorico *et al* 2014 for details). Stock values in kcal are then cumulated over all the N_p available food products to obtain an indication of the total energy-equivalent stocked in food in a country or region at a given time, $\tilde{S}_i(t) = \sum_{p=1}^{N_p} \tilde{S}_i^p(t)$. As mentioned above, the errors in the estimate of product-specific stocks (\tilde{S}_i^p) tend to compensate each other in the aggregation process across products, thus reducing the uncertainty associated to the aggregated variable. Also note that the aggregated time series will differ from zero (positive) in all years, because years with a null stock will not be synchronous for all commodities. Per-capita stock values are obtained as the ratio of $\tilde{S}_i(t)$ with the population $p_i(t)$ in the i th region in year t , $\tilde{s}_i(t) = \tilde{S}_i(t)/p_i(t)$. We aggregate country-specific stock data into nine regions, corresponding to the geographic areas proposed by the World Bank (<http://worldbank.org/en/region/eca>). Regional stock values are calculated as the sum of country-specific stock values ($\tilde{S}_i(t)$) for the countries within each region; the corresponding per-capita stock values are obtained as ratios between $\tilde{S}_i(t)$ and the regional population.

Expected future changes in food stocks

To obtain a statistically-sound representation of food stock dynamics, we hypothesize that the variations in per-capita stocks, $\tilde{s}(t)$, can be treated as realizations of a Wiener process with Langevin equation

$$\frac{d\tilde{s}(t)}{dt} = \sigma \cdot \varphi(t), \quad (1)$$

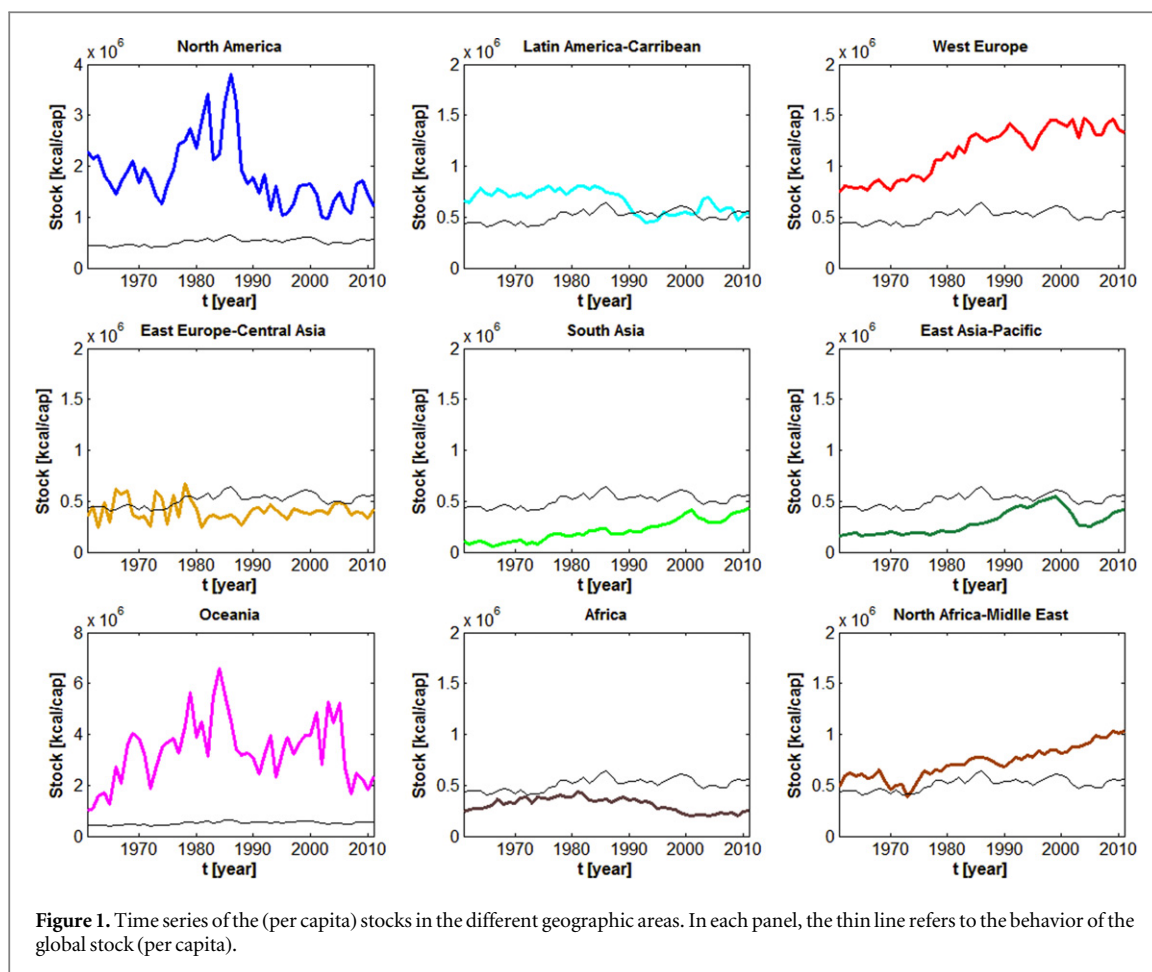
where σ is a parameter magnifying the strength of the noise, and $\varphi(t)$ is a Gaussian white noise term (with unit noise intensity). Our hypothesis is that equation (1) holds not only at the global scale but also for each macro-region, though with different σ values. The hypothesis that a time series is a realization of a Wiener process may be tested by considering the increments of the process, $\delta(t) = \tilde{s}(t) - \tilde{s}(t-1)$, and verifying that the following four conditions are met (Van Kampen 2007): (i) the mean of the increments is not significantly different from zero (i.e., the process is stationary); (ii) the increments are mutually independent; (iii) the increments are normally distributed; and (iv) the standard deviation of the increments is constant, i.e. σ is not a function of time (homoscedasticity hypothesis).

We test the zero-mean hypothesis (stationary process) with a student-t test (Sheskin 2011), where the t-variable is obtained as the ratio of the sample mean (of the increments) to the standard deviation of the mean. For a given significance level, α , limit values are obtained as the $\alpha/2$ and $(1 - \alpha/2)$ quantiles of a t-student distribution with $(n - 2)$ degrees of freedom, where n is the length of the available sample. Independency is tested by verifying that the increments are uncorrelated, building on the equivalence of dependence and correlation in a Gaussian setting. A standard t-test for the hypothesis that the correlation coefficient r is zero may thus be used in this case (Sheskin 2011). The t variable is calculated as $\sqrt{(n - 2)/(1 - r^2)}$. Limit values for the test are again obtained as the quantiles of a t-student distribution with $(n - 2)$ degrees of freedom. The same test statistics can also be used to verify the statistical significance of the cross correlation between stock increments in different regions, where the cross-correlation coefficient, r_{xy} , is used in place of the auto-correlation coefficient r . The third hypothesis is that the increments follow a Gaussian distribution function: this hypothesis is verified by using an Anderson-Darling goodness of fit test (D'Agostino and Stephens 1986), where the test statistics A^2 measures the distance between the hypothetical Gaussian distribution and the empirical distribution function, giving more weight to the discrepancies in the tails of the distribution. This is a one-tail test, and the limiting values can thus be obtained as the $(1 - \alpha)$ quantile of the A^2 distribution, suitably modified to account for the fact that the Gaussian parameters are estimated using the same sample (Sheskin 2011). Finally, the homoscedasticity hypothesis is verified by performing a White test (White 1980): the squared increments are regressed versus time, and the coefficient of determination R^2 is estimated for this regression; the test statistic is nR^2 , and the limit value for the one-tail test is obtained as the $(1 - \alpha)$ quantile of a chi-squared distribution with 2 degrees of freedom.

Results

Food stock dynamics in the last half a century (1961–2011)

We find that, despite their random fluctuations about the mean (see figure 1), per-capita regional food stocks have remained approximately steady, as demonstrated by the stationarity test discussed below. This result indicates that global food reserves are increasing at about the same rate as population growth. Their average value is 5.1×10^5 kcal cap⁻¹, which corresponds to a food stock able to feed the global population for approximately 175 days, with a per-capita daily average consumption of 2880 kcal d⁻¹ (FAO 2014). A 175 day stock is larger than the grain reserves typically reported by other authors



(EPI 2013). This discrepancy might be due to the larger number of products considered in our study (92 food commodities and not only grains), the new methodology used to estimate food stocks from annual variations, and the stock data analyzed (FAO 2014), which refer to the end of the year rather than the beginning of the cropping season.

The dynamics of food reserves exhibit different properties across the World's regions included in this study. Per-capita food stocks are relatively large and volatile in North America and Oceania; the large volatility is partly explained by the small population of these regions, and the strong involvement in international trade (D'Odorico *et al* 2014, MacDonald *et al* 2015). These major exporting regions exhibit disproportionately large stocks (with respect to the size of their own population). As such, they can afford to vary their exports according to the needs and opportunities of the global market. While doing so, their reserves may undergo strong fluctuations without compromising, however, the regional food security because of their high food stocks per-capita. South Asia, North Africa and Middle East show a positive trend in per-capita stocks, which, however, is only weakly significant (see table 1 below). East Asia and Pacific have a similar behavior up to 1999, followed by a sharp drop in food stocks because of policy decisions aiming at a reduction in food reserves in China and India (World

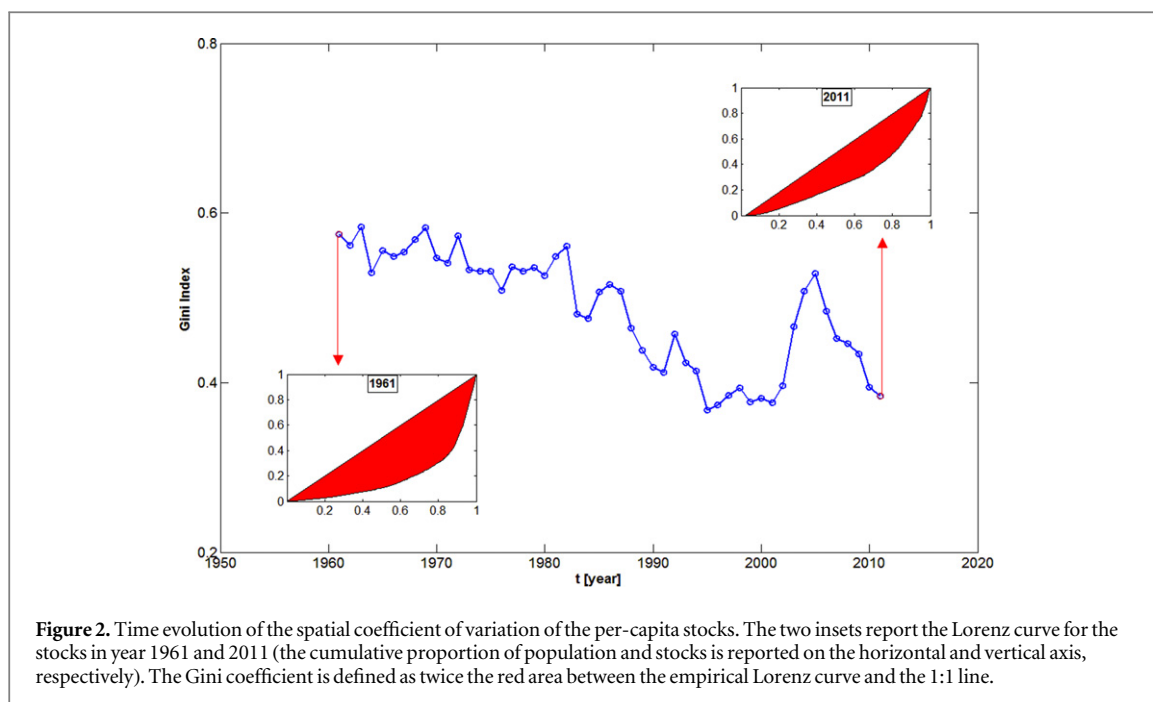
Bank 2012). In Latin America and the Caribbean, West Europe, and Africa the per-capita stocks exhibit relatively weaker interannual fluctuations, which is a symptom of a less dynamic stock management, scarce reserves (in Africa), a conservative food stock policy (in West Europe), or a combination of the two. Finally, the region encompassing Europe and Central Asia includes countries which were formerly part of (or under the influence of) the Soviet Union; thus, in this region the transition between more volatile food stocks (until 1980) to a 'smoother' behavior (after 1990) was likely due to the collapse of the Soviet Union (Sharples and Martinez 1993). Stocks in Africa have remained below the 100 day reserve threshold (i.e., 2.88×10^5 Kcal) since the mid-90s, while East Asia and Pacific and South Asia have kept small stocks until the late 1980s-early 1990s, and increased them since then.

There is an overall strong spatial heterogeneity (figure 2) in per-capita food stocks, with differences spanning one order of magnitude, from 2.5×10^5 kcal cap⁻¹ in Africa to 2.4×10^6 kcal cap⁻¹ Oceania in 2011.

Heterogeneity in the global distribution of food stocks (among countries) is here measured using the Gini coefficient, a metric that may vary from 0 (perfect homogeneity) to 1 (perfect heterogeneity, all stocks owned by a single person). We found that the Gini

Table 1. Statistical verification of the hypotheses justifying the adoption of a Wiener process to model per-capita stocks. For stationarity and independence, we report the values of t-statistics, with limit values 1.68 (10% significance), 2.01 (5%), and 2.68 (1%). For the normality test the reported values are those of the Anderson-Darling statistic, with limit values 0.66 (10%), 0.79 (5%), and 1.09 (1%). Finally, the values of the White test-statistic are reported on the bottom line of the table, with limit values 4.60 (10%), 5.99 (5%), and 9.21 (1%). (*) indicates cases when the null hypothesis should be rejected at a 10% level, (**) at a 5% level, and (***) at a 1% level.

	North America	Latin America and Caribbean	West Europe	Europe and Central Asia	South Asia	East Asia and Pacific	Oceania	Africa	North Africa and Middle East	World
STATIONARITY	-0,35	-0,35	1,11	-0,06	1,90(*)	1,27	0,18	0,03	1,65	0,49
INDEPENDENCE	-0,06	0,12	-1,57	-1,43	1,54	4,98(***)	-2,22(**)	-1,46	-0,46	0,53
NORMALITY	0,49	0,26	0,27	0,67(*)	0,67(*)	2,35(***)	0,22	0,43	0,34	0,50
OMOSCEDASTICITY	0,00	2,49	4,97(*)	0,02	3,18	6,59(**)	1,32	3,10	7,00(**)	0,13



coefficient of food stocks fluctuated around 0.5–0.6 for the first 20 years of record and, then, decreased to about 0.3 in year 2000, followed by an up-and-down fluctuation over the last decade. We observe an overall tendency toward a more homogeneous global distribution of food stocks among countries (figure 2). Heterogeneity, however, is still rather strong: in 2011, 50% of the stocks were in the ‘hands’ of 20% of the global population (compared to 70% of the stocks controlled by countries with 20% of the global population in 1961). Interestingly, the temporal behavior of the Gini coefficient and the deflated FAO price index exhibit significant similarities, testified by a cross-correlation coefficient equal to +0.41, suggesting that a more homogeneous distribution of food stocks has a moderating effect on the food price dynamics. Conversely, it can be argued that food price spikes induce an unequal distribution of resources that is reflected in more heterogeneous stock distributions.

Cross-correlations, r_{xy} , between stock increments in different regions are generally not statistically significant (see methods section). Only, the East Asia and Pacific macroregion exhibits significant correlations, with South Asia ($r_{xy} = 0.30$) and Latin America and Caribbean ($r_{xy} = -0.33$). Geographic contiguity likely explains the former case, while the latter may result from the strong food exports from South America (particularly Brazil and Argentina) to China (D’Odorico *et al* 2014, MacDonald *et al* 2015).

Typically, the one-year lagged cross-correlations are also not statistically significant, except for the case of West Europe, whose stock increments are correlated with those of Oceania ($r_{xy} = 0.43$) in the previous year. Likewise, lagged cross-correlation exists between East Asia and Pacific and South Asia ($r_{xy} = 0.43$). In both cases, such correlations are likely

due to the prevalent net exports from Oceania and South Asia to West Europe and East Asia and Pacific, respectively (MacDonald *et al* 2015).

Future stock dynamics

As a first step, we report the results of the tests aimed at verifying the hypothesis that the variations in per-capita stocks, $\tilde{s}(t)$, can be treated as realizations of a Wiener process. The results of the four tests described in the methods section are reported in table 1 for the nine macro-regions and the entire world. In the case of Europe and Central Asia data before 1990 are discarded from the analysis because of the presence of a discontinuity in the time series likely due to the collapse of the Soviet Union.

In four out of ten cases, including the entire world, the hypotheses are acceptable at all significance levels, thus providing full support for the adoption of the Wiener process as a model for the stochastic variations in food stocks per-capita. Other three macroregions present only weak deviations (at a 10% level) from the null hypotheses: in these cases the Wiener process can still be assumed to hold, especially if we account for the fact that rejection of the null hypotheses at 10% level is indeed expected in 4 cases out of 40 even when the hypothesis is true (type I error). Oceania and North Africa and Middle East present more significant (5% level) hints that some of these hypotheses should be rejected, but in each case rejection would be limited to only one of the four tests. Thus in these cases there is no strong evidence for the failure of the Wiener process as a possible representation of food stock dynamics. In contrast, 3 out of the 4 hypotheses are strongly rejected for the region East Asia and Pacific, thereby invalidating the use of the Wiener process in the

representation of food stock dynamics in this macro-region. The reason why the Wiener process is unable to model these dynamics is likely due to the sharp drop in per-capita stocks that has occurred in this region—particularly in China (Von Braun 2007, World Bank 2012)—in the years 1999–2004. Thus, the smoothly varying Wiener process cannot capture these dynamics. Despite this exception, the support to this very simple stochastic representation of food stocks dynamics is surprisingly strong, likely because of the aggregation of food stocks, that helps smoothing and normalizing the dynamics.

We stress that an even simpler representation could have been adopted as a model of stock dynamics: in fact, one could consider modeling the time series in figure 1 as linear trends with a superimposed noise, characterized by the probability distribution of the observed residuals (defined as the difference between the real data and the trend line). However, this representation of the process is not statistically well-grounded: in fact, it is required that the residuals are mutually independent in order to properly estimate the trend line coefficients, verify the significance of the coefficients, and produce a probabilistic prediction of a future value (Kendall and Stuart 1977). In the present case, residuals are indeed significantly auto-correlated (when the trend line is estimated using the least squares method), with correlation coefficients significantly different from zero at a 0.1% level for all regions (including the world) except Europe and Central Asia. For example, the correlation coefficient of the residuals at the global scale is 0.78, corresponding to a t -value 8.69 (which is much larger than the corresponding limit values reported in the caption of table 1).

We can now use the stochastic model (1) to determine the probability of occurrence of future changes in food stocks and investigate their temporal evolution using the value observed in 2011 as the initial condition, \tilde{s}_0 . Examples of possible future realizations of the process are shown in figure 3(a). For a fixed lag time t after 2011, the probability density function of $\tilde{s}(t)$ is (Van Kampen 2007)

$$p_{\tilde{s}}(\tilde{s}(t)) = \frac{1}{\sigma\sqrt{2\pi t}} \exp\left[-\frac{(\tilde{s}(t) - \tilde{s}_0)^2}{2\sigma^2 t}\right]. \quad (2)$$

Alternatively, one can fix a threshold value \tilde{s}_{th} and determine the probability distribution of the first-passage times, τ , of the threshold for a process starting at \tilde{s}_0 . In other words, τ is the time that will take for per-capita stocks to drop below the threshold value. The corresponding probability density function is (Van Kampen 2007)

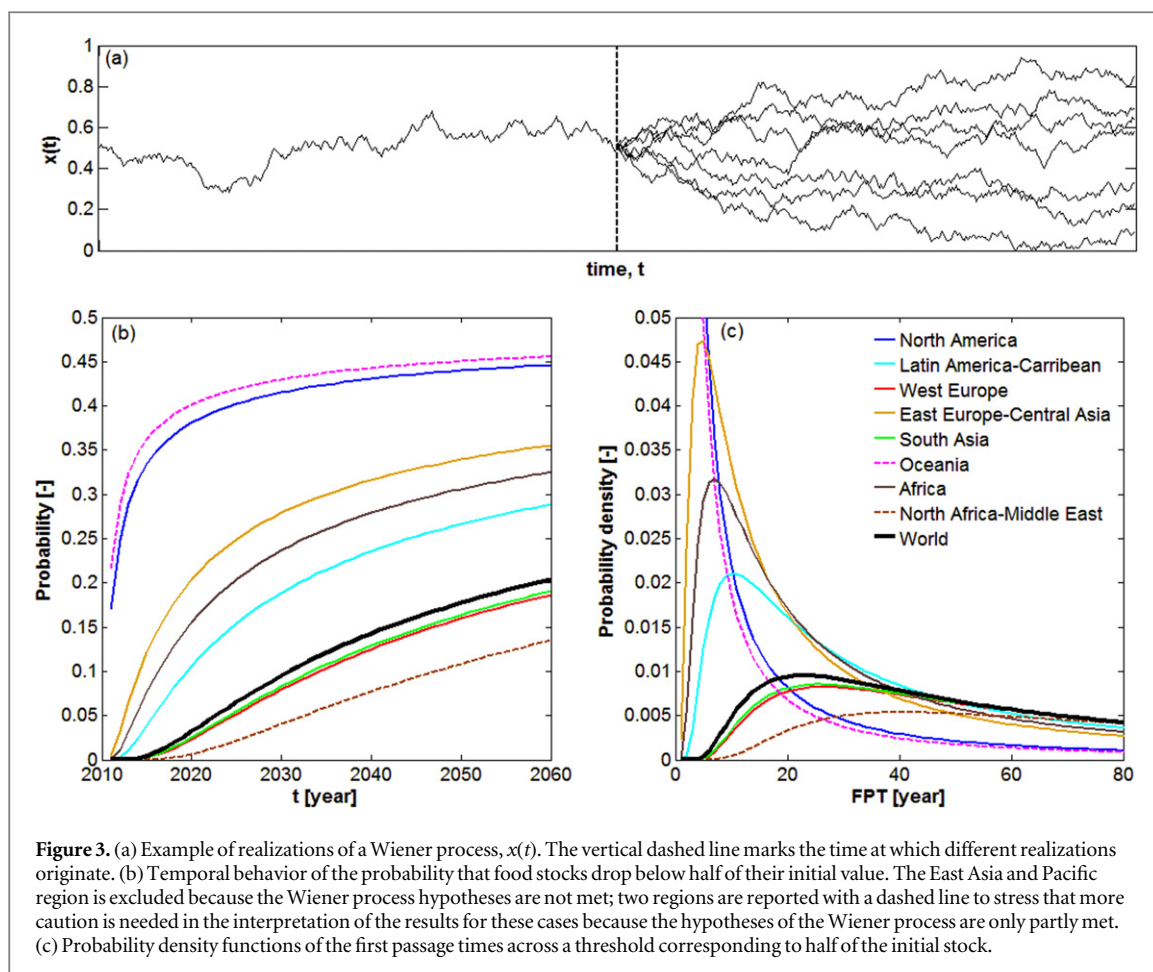
$$p_{\tau}(\tau) = \frac{|\tilde{s}_0 - \tilde{s}_{th}|}{\sigma\sqrt{2\pi\tau^3}} \exp\left[-\frac{(\tilde{s}_0 - \tilde{s}_{th})^2}{2\sigma^2\tau}\right]. \quad (3)$$

We use (2) and (3) to calculate the probability that per-capita food stocks drop below a threshold value,

\tilde{s}_{th} , which is expressed as a fraction of the initial value, \tilde{s}_0 (figures 3(b) and (c)). The probability that the per-capita stock drops below \tilde{s}_{th} nonlinearly increases in time, as expected for a Wiener process. We concentrate our attention in particular on the stock-halving probability by year 2050—i.e. on the probability that the global per-capita food stocks will be less than $\tilde{s}_0/2$ in 2050—being the stock halving probability an intuitive measure of the natural variability of the process. At a global scale we find that the halving probability in 2050 is 0.2; at a regional scale, we find that Western Europe, North Africa and Middle East, and South Asia have very stable stocks, with rather low probabilities for the stocks to be halved by 2050. In contrast, North America and Oceania have rapidly fluctuating food reserves, with rather large probabilities to see their stock drop below half of their initial values in the near future. It should be stressed, however, that in these regions the initial per-capita stocks are relatively large. These results are confirmed by the representation of the probability distribution of the first passage times across the threshold $\tilde{s}_0/2$, (figure 3(b)). These distributions are L-shaped for North America and Oceania, showing a high probability of a 50% reduction (or increase, since the dynamics are symmetrical with respect to \tilde{s}_0) in per-capita food stocks. In other regions the probability distribution of first passage times is unimodal, with the mode (i.e., the most likely number of years it will take for the stocks to be halved since 2011) lying in the 5–40 years range. The combination of very low stock levels (see figure 1) and a low mode (about ten years) makes Africa particularly vulnerable to food insecurity.

Discussion

In the course of human history societies have often relied on food reserves as a means to cope with crop failures and associated food shortage. In recent years the intensification of food trade has allowed some countries to respond to food scarcity by importing agricultural products from other regions of the world either through trade or food aid (Porkka *et al* 2013, D’Odorico *et al* 2014). The uncertainty and unreliability of international food markets during the recent food crises (Fader *et al* 2013), however, have highlighted the possible important role that stocks can still play in national and regional food security. This paper provides a comprehensive analysis of food stocks accounting for a large number of food commodities. The calculation of global and regional food stocks is a difficult task because of uncertainties associated with data sources, accounting protocols and whether stocks are recorded at the beginning or the end of the growing season. In this study we have developed a consistent, conservative analysis of FAO data, considering a broad range of products. Aggregation over different products/countries allows us to obtain robust results,



notwithstanding the high level of uncertainty in the original data. Moreover, summing up over different products allows us to determine the total food stocks in terms of their caloric content, though we acknowledge all commodities are not the same in terms of their nutritional value. Our focus on the energetic properties (i.e., food calories) of stocks is an important first step in the quantitative assessment of the dynamics of food reserves. Other factors (e.g., protein or vitamin content of the food) that are also important determinants of the nutritional aspects of food security will need to be included in future studies of food stocks.

Our study provides a consistent reconstruction of aggregated food stock data, but other relevant outcomes emerge from the analysis of the data: Through a detailed statistical analysis we demonstrate how in most cases no significant trends exist in food stocks. Previous studies have documented a decline in the reserves of specific grains over the last few decades (Wright 2011, Cafiero *et al* 2015). While we agree that per capita grain reserves are declining, we challenge the widespread notion that food reserves are shrinking. We show that, if we consider a larger number of products (accounting for all the major food commodities), adopt a new methodology to estimate food stock data, but it would require access to higher-quality

year stocks, regional and global food reserves do not exhibit a decline.

As a further contribution, we developed a comprehensive analysis of (per-capita) food stock fluctuations to find that their dynamics can be expressed as the sum of random independent variations. In other words, the dynamics of food stocks (per-capita) can be described by a Wiener process both at the global and (with some exceptions) at regional scales. This allows us to predict, in a probabilistic sense, the possible future dynamics of the food system. Globally, the probability that per-capita stocks will be halved by 2050 is about 20%, with some strong regional differences: the trade-dependent regions of Western Europe and North Africa and Middle East have smaller halving probabilities and smaller per-capita stocks, while North America and Oceania (major crop producers and exporters) have greater halving probabilities and greater per-capita stocks than the global average. Thus regions with bigger (smaller) stocks can afford stronger (weaker) fluctuations. The main exception is Africa, which exhibits low per-capita stocks and relatively high probability of stock halving by 2050. The strength of our findings is in their strong reliance on data; other interesting findings could result from the analysis of disaggregated stock data, but it would require access to higher-quality stock data.

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References

- Abbott P 2013 *Improved Methodology for Estimation of Food Stocks* FAO
- Adger W N 2006 Vulnerability *Global Environ. Change* **16** 268–81
- AMIS 2015 *Stocks and Utilization* Agricultural Market Information Systems (<http://amis-outlook.org/>)
- Ben-Ari T and Makowski D 2014 Decomposing global crop yield variability *Environ. Res. Lett.* **9** 114011
- Bobenrieth E, Wright B and Zeng D 2012 *Stock-to-Use Ratios as Indicators of Vulnerability to Spikes in Global Cereal Markets* AMIS IG-12/4
- Brown L R 2013 *Full Planet, Empty Plates: The New Geopolitics of Food Scarcity* (New York: W.W. Norton & Company)
- Cafiero C, Bobenrieth H E S A, Bobenrieth H J R A and Wright B D 2015 Maximum likelihood estimation of the standard commodity storage model: evidence from sugar prices *Am. J. Agric. Econ.* **97** 122–36
- Calderini D F and Slafer G A 1998 Changes in yield and yield stability in wheat during the 20th century *Field Crop. Res.* **57** 335–47
- Carr J A, Seekell D A and D'Odorico P 2015 Inequality or injustice in water use for food? *Environ. Res. Lett.* **10** 024013
- Carter C A, Rausser G C and Smith A 2011 Commodity booms and busts *Annu. Rev. Resour. Econ.* **3** 87–118
- Cassidy E S, West P C, Gerber J S and Foley J A 2013 Redefining agricultural yields: From tonnes to people nourished per hectare *Environ. Res. Lett.* **8** 034015
- D'Agostino R B and Stephens M A 1986 *Goodness-of-fit Techniques* (New York: Dekker)
- D'Odorico P, Laio F and Ridolfi L 2010 Does globalization of water reduce societal resilience to drought? *Geophys. Res. Lett.* **37** L13403
- D'Odorico P, Carr J, Laio F, Ridolfi L and Vandoni S 2014 Feeding humanity through global food trade *Earth's Future* **2** 458–69
- Davis K F, D'Odorico P and Rulli M C 2014 Moderating diets to feed the future *Earth's Future* **2** 559–65
- EPI 2013 *Grain Consumption and Stocks 1960–2012* Earth Policy Institute (Bases on data from US Department of Agriculture, Production, Supply, & Distribution) (http://earth-policy.org/data_center/C24)
- Fader M, Gerten D, Krause M, Lucht W and Cramer W 2013 Spatial decoupling of agricultural production and consumption: quantifying dependences of countries on food imports due to domestic land and water constraints *Environ. Res. Lett.* **8** 014046
- FAO 2014 Food security indicators (<http://fao.org/economic/ess/ess-fs/it/>)
- FAO 2015 Faostat online database (<http://faostat.fao.org/default.aspx>)
- Foley J A *et al* 2011 Solutions for a cultivated planet *Nature* **478** 337–42
- Fraser E D G, Legwegoh A and Krishna K C 2015 Food stocks and grain reserves: evaluating whether storing food creates resilient food systems *J. Environ. Stud. Sci.* **5** 445–58
- Fraser E D G, Mabee W and Függe F 2005 A framework for assessing the vulnerability of food systems to future shocks *Futures* **37** 465–79
- Godfray H C J, Beddington J R, Crute I R, Haddad L, Lawrence D, Muir J F, Pretty J, Robinson S, Thomas S M and Toulmin C 2010 Food security: the challenge of feeding 9 billion people *Science* **327** 812–8
- Gouel C 2013 Optimal food price stabilization policy *Eur. Econom. Rev.* **57** 118–34
- Kastner T, Rivas M J I, Koch W and Nonhebel S 2012 Global changes in diets and the consequences for land requirements for food *Proc. Natl Acad. Sci. USA* **109** 6868–72
- Kendall M G and Stuart A 1977 *The Advanced Theory of Statistics* (New York: MacMillan)
- Lilliston B and Ranallo A (ed) 2012 *Grain Reserves and the Food Price Crisis: Selected Writings from 2008–2012* (Minneapolis: Institute for Agriculture and Trade Policy)
- MacDonald G K, Brauman K A, Sun S, Carlson K M, Cassidy E S, Gerber J S and West P C 2015 Rethinking agricultural trade relationships in an era of globalization *Bioscience* **65** 275–89
- Porkka M, Kummu M, Siebert S and Varis O 2013 From food insufficiency towards trade dependency: a historical analysis of global food availability *PLoS One* **8** e2714
- Puma M J, Bose S, Young Chon S and Cook B I 2015 Assessing the evolving fragility of the global food system *Environ. Res. Lett.* **10** 024007
- Sharples J A and Krutzfeldt J 1990 World grain stocks *US Dept. Agriculture, Bulletin No.* 594
- Sharples J A and Martinez S 1993 The role of stocks in world grain market stability *US Dept. Agriculture, Report* FAER-248
- Sheskin D J 2011 *Handbook of Parametric and Nonparametric Statistical Procedures* 5th edn (London: Chapman and Hall)
- Simelton E 2011 Food self-sufficiency and natural hazards in China *Food Secur.* **3** 35–52
- Suweis S, Carr J A, Rinaldo A, Maritan A and D'Odorico P 2015 Resilience and reactivity of global food security *Proc. Natl Acad. Sci. USA* **112** 6902–7
- Suweis S, Rinaldo A, Maritan A and D'Odorico P 2013 Water-controlled wealth of nations *Proc. Natl Acad. Sci. USA* **110** 4230–3
- Tilman D, Balzer C, Hill J and Befort B L 2011 Global food demand and the sustainable intensification of agriculture *Proc. Natl Acad. Sci. USA* **108** 20260–4
- UN 2011 *Human Development Report 2011—Sustainability and Equity: a Better Future for All* United Nations Development Program
- Van Kampen N G 2007 *Stochastic Processes in Physics and Chemistry* 3rd edn (Berlin: North-Holland)
- Von Braun J 2007 *The World Food Situation* (Washington: International Food Policy Research Institute)
- White H 1980 A heteroskedasticity-consistent covariance matrix estimator and a direct test for heteroskedasticity *Econometrica* **48** 817–38
- Wiggins S and Keats S 2009 *Grain Stocks and Price Spikes* (London: Overseas Development Institute)
- World Bank 2012 Using public foodgrain stocks to enhance food security *Report n.* 71280-GLB
- Wright B D 2011 The economics of grain price volatility *Appl. Econom. Perspect. Policy* **33** 32–58
- Wright B D and Cafiero C 2011 Grain reserves and food security in the Middle East and North Africa *Food Secur.* **3** S61–76