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Stochastic Model Development and Price Volatility Analysis

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Abstract

STOCHASTIC MODEL DEVELOPMENT AND PRICE VOLATILITY ANALYSIS

Shinichi Taya, OECD

The OECD-FAO Agricultural Outlook provides mid-term projections of global agricultural markets simulated by the AGLINK-COSIMO model. While the projections typically present a deterministic outlook for markets that are conditional on a set of assumptions, recent experience of highly turbulent markets has renewed interest in quantitative assessment of price volatility by stochastic simulations using the AGLINK-COSIMO model. Improvements in the methodology of stochastic analyses are pursued and implemented. As an application, the impact of crop yield shocks on price volatility is studied. Since the concurrent reduction in production in different countries is deemed as one of the factors of the price spike in 2007/08, the contribution of correlation of yield shocks to price volatility is measured. This paper shows that correlation effects account for a significant portion of price volatility for coarse grains and wheat.

Key words: Stochastic simulations, volatility, variability, coarse grains, rice, wheat, correlation.

Acknowledgement

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Executive Summary

This report is one of a series of Secretariat studies aimed at improving the stochastic capacity of the OECD-FAO AGLINK-COSIMO model, and the ways of interpreting and presenting the results. Stochastic analysis is one means to improve our understanding of the uncertainties around medium-term market projections and the relative importance of the drivers of market volatility. There is also a growing interest in more sophisticated scenario analysis using this tool.

The main messages from this report include:

- Previous work of the Secretariat in this area shows that crop yields appear to be the most important driver of price volatility for wheat, coarse grains and rice.
- The methodology used in the previous work tended to underestimate crop yield variability.
- The new formula for stochastic yields developed for this study provides a better reflection of historical yield variability, eventually improving the simulations of price volatility. A larger portion of historical price volatility was replicated (70% for coarse grains and 89% for wheat).
- Risk of multivariate yield distribution is decomposed into three components to highlight the role of concurrent shocks to different crops and countries :
  - Specific risk represented by yield deviation from trend (standard deviation)
  - Regional correlation risk - the tendency of yields of crops within a region to move together
  - Global correlation risk - the tendency of yields of crops between different regions to move together
- Regional and global correlation effects combined account for 40% and 46% of total price volatility for coarse grains and wheat, respectively. The impact of correlation risk is marginal for rice.
- The correlation risk has a larger impact on price volatility for wheat than for coarse grains. As wheat production is geographically more diverse, the risk of shocks to different producing countries plays a greater role in the global wheat market.
- Diversification of supply sources can reduce price volatility if their exposure to concurrent shocks is very limited, while this mitigating effect disappears with correlation risk.
- The higher yield variability 2001-10 increased price volatility 19% for coarse grains and 90% for wheat but was negligible for rice in simulations compared with the low variability 1992-2000.
- The main source of the higher volatility in the high risk period was higher correlation rather than higher standard deviation, which confirms the importance of concurrent shocks to different crops and countries for price volatility.
- Areas for further work might include accounting for dynamic supply and demand response to yield shocks/price volatility, examining the impact of structural changes

(e.g. technological innovation, climate change) on yield variance and covariance, and the impact of yield variability on variables other than price (e.g. trade, land use, stock levels).

- Price volatility in this study is limited to annual changes. Variation in a shorter period of time is not addressed. Risk factors other than variable crop yields are not examined. Impacts of oil prices, exchange rates and policies are not considered in this paper.

Background

The OECD-FAO Agricultural Outlook and related AGLINK-COSIMO model scenario analyses provide quantitative projections of agricultural production, use, trade and, perhaps most importantly, commodity prices. Policy makers generally prefer the deterministic point estimates normally provided by such analysis over price ranges that are more difficult to interpret. However, the increased price volatility of agricultural markets in recent years has raised concern over the uncertainty around such point estimates. These concerns have led to a renewed interest in stochastic analysis, which is a useful tool for examining the level of uncertainty and the main driving forces behind such price volatility.

The current study builds on an earlier stochastic study of risk and price volatility using the AGLINK-COSIMO model that was declassified at the May 2011 meeting of the APM Working Party [TAD/CA/APM/WP(2010)31/FINAL]. The earlier work was a first step in developing the partial stochastic modelling capabilities of AGLINK-COSIMO, while concluding that crop yields[1] were the main exogenous factor explaining price volatility for maize (almost 70%) - somewhat less for wheat and rice (major food crops). As this work was well received and apparently of high interests to many delegates, further development of the model and additional analysis of price volatility was undertaken for this paper.

Another document submitted to the November 2011 APM meeting [TAD/CA/APM/WP(2010)28] presents the results of selected scenarios and stochastic experiments which examine the impacts on world wheat prices of income growth in the large emerging economies, lower levels of global stocks and an international stockholding mechanism. This work benefits from using the latest generation of the AGLINK-COSIMO model (post 2009-10 review) and the 2011-20 baseline as well as additional modifications to the stochastic analysis methodology.

The objective of this paper is two-fold. First, further improvements in methodology of stochastic simulations are pursued. Since stochastic simulations are a combination of economic modelling and statistical techniques, the result of experiments is considered to be sensitive not only to the model used but also to the methodology employed to generate random variables that are used as proxies of risk and uncertainties. It is thus of significant relevance to review the stochastic approach used in previous analysis using the Aglink model and test whether alternatives might provide more robust results. Second, as an application of the improved methodology, price volatility analysis is addressed in the second part of this paper with a special emphasis on external production risk. Given that crop yield risk, which was found to be one of the most significant factors to price volatility in the former work, this driver is the focus of the analysis.

1 The term “yield” always refers to output per area with its unit being ton per hectare throughout this paper.

1. Stochastic model development

1.1 Methodological improvements

New methodology to generate stochastic crop yields

The AGLINK-COSIMO model is a forward-looking medium term economic model which simulates ten years into the future. It is necessary to feed into the model projections for exogenous variables (population growth, GDP growth, oil prices, etc) as a set of assumptions. While a single set of assumed projections are used for deterministic simulations, multiple sets of exogenous variables, which are generated by random samplings and thus represent risk and uncertainty, are fed into the model for stochastic experiments. Simulations are run for each set of assumptions and multiple sets of solutions are provided. Implications of risk and uncertainty are inferred from statistical information of the random outputs of simulations. As such, the methodology of random draws is one of the key issues in stochastic simulations.

In the previous stochastic works by the Secretariat, truncated random walk specification is chosen for crop yields. In this approach, a multivariate normal distribution is applied for the first differences of yields (Table 1.1). Variable yields are obtained by summing up the random first differences. Since this summation of normal random variables generates a random walk, which is to be very volatile as it evolves along the time span[2], upper and lower bounds are set to avoid extremely deviated values (truncation). Because of the strong tendency of random walks to deviate, the elimination of extreme values above or below may be frequent. For the present work, this tendency could result in underestimation of the underlying variability of crop yields. As yield variability is to be reflected in price volatility through simulations, it is important to examine this underestimating effect.

Table 1.1 Comparison of methodologies

	Previous methodology	New methodology
Model and database	Agricultural Outlook 2010-2019	Agricultural Outlook 2011-2020
Number of draws	150	500
Regional blocks	Africa, Asia, Europe, North America, South America, Oceania,	North Africa and Middle East, Sub-Saharan Africa, East Asia, South Asia, Southeast Asia, West Asia, Europe, North America, South America, Oceania
Stochastic yields	Coarse grains, rice, wheat	Coarse grains, rice, wheat
Formula for yields	$d(yield)_t$ = $yield_t$ – $yield_{t-1}$ $d(yield)_t$ following normal distribution yields truncated to upper/lower bounds	log(yield) = trend + residual residual following normal distribution no truncation

2 Standard deviation of a random walk is a linearly increasing function of time. In the context of this study, yield variability becomes ten times higher in 2020 than the level in 2011 if not truncated.

To probe this question, an alternative approach is tested and comparisons are made between the two methods. As a new specification, crop yields are assumed to be trend plus normally distributed disturbances in logarithms (Table 1.1). Truncation is not necessary in this approach as the formula is more stable around the trend and ensures non-negativity of yields. Detailed scrutiny of the approaches is implemented in the next section of the paper.

Regional disaggregation and increased sample size

Technical improvements other than yield specification are implemented as well. In the earlier study, regional blocks were defined and correlation of yields was allowed only for countries within a given block. This assumption is maintained, while the definition of blocks is refined to better reflect regional specificity (Table 1.1). For example, a block "Asia" was deemed too large to reflect the diversity of country experiences within this region. For this reason, it was disaggregated into four distinct blocks: East Asia, South Asia, South East Asia and West Asia. A further improvement is that the use of the updated methodology of the troll software allows a substantial increase in the number of simulations or random draws (from 150 to 500) that can be run. The larger number of random draws increases the sample size and makes the stochastic experiment more robust, thus strengthening the credibility of the scenario results.

1.2 Test of methodologies for stochastic yields

The test of the alternative new specification of yields is implemented by simulations with a comparison of its ability to replicate price volatility against the previous truncated random walk approach. Stochastic yields are generated by the two formulae (Table 1.2) and input into the model and market clearing prices are solved. Table 1.3 and Figure 1.1 summarise price volatilities obtained by the two methodologies. Variability and volatility is measured by standard deviation of year-to-year changes of prices over a specified period.[3] The listed variabilities and volatilities[4] in Table 1.2, Table 1.3 and Figure 1.1 are standard deviation of seven observations of annual changes over 2014-2020.

Table 1.2. Simulated yield variability over 2014-2020 by two methodologies

	Previous formula	New Formula	Historical 1976-2010
World CG yield variability	3.3%	4.2%	7.6%
World RI yield variability	1.8%	1.7%	1.9%
World WT yield variability	1.9%	3.7%	4.8%

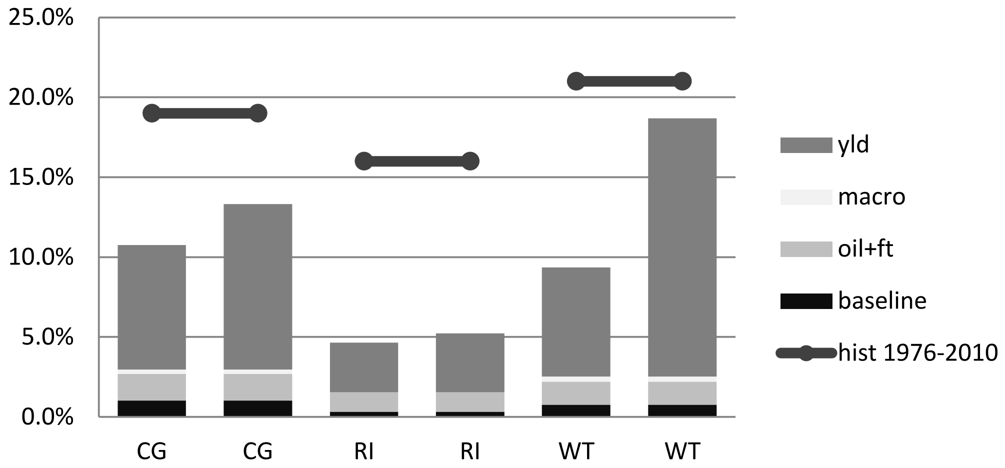
3 For example, volatility of x over 2001-2010 is defined as the standard deviation of $\ln(x_{2001}/x_{2000})$, $\ln(x_{2002}/x_{2001})$, $\cdots$, $\ln(x_{2010}/x_{2009})$. Volatility over the projection period is measured over the seven years 2014-2020 instead of the entire projection period 2011-2020. As crop prices are projected to fall over time from the high levels in recent years in the *deterministic* baseline, volatility of prices is inflated if calculated for 2011-2020. Since the impacts of *stochastic* factors on price volatility are the concern of the study, the first three years are not counted in volatility calculation to remove this effect.

4 The term "variability" is used for variation in yields while the term "volatility" is reserved to refer to variation in prices.

Table 1.3. Simulated price volatility over 2014-2020 by two methodologies

	Previous formula	New formula	Historical 1976-2010
Coarse grains price volatility	10.8%	13.3%	19.0%
Rice price volatility	4.6%	5.2%	16.0%
Wheat price volatility	9.3%	18.7%	21.0%

Figure 1.1 Comparison of simulated price volatility in 2014-2020 by two methodologies



1) Left bars are the previous methodology; right bars are the new methodology.

2) Only yield variability is examined; no changes to oil prices and macroeconomic variables in this study.

Less variable yields should result in less volatile prices. Therefore, the methodologies in this stochastic analysis that best replicate historical yield variability are preferable.

The anticipated underestimation of yield variability due to truncation is confirmed and remedied for coarse grains and wheat by the new methodology, with the trend plus residual formula without truncation improving yield variability significantly. The most improvement is for wheat, with its yield variability in median being 3.7 % by the new methodology while 1.9% by the previous methodology (Table 1.2). Although little change is observed for coarse grains yield variability in terms of median, the ten percentile and the ninety percentile are shifted upward by the new specification, ensuring greater variability also for coarse grains yields (Table 1.2). As a direct consequence of ameliorated replication of variable yields, the amount of price volatility explained by yield variability is significantly improved for coarse grains (from 10.8% to 13.3%) and wheat (from 9.3% to 18.7%) by the new methodology (Table 1.3), successively counting for 70% and 89% of their historical volatility respectively (Figure 1.1).

In contrast with the two commodities, no significant gain is observed for rice by the new methodology. The variability of truncated rice yields is comparable to the one obtained by the new formula without truncation. If a random walk path is moderately volatile, truncation dampens its variability significantly, creating a path flat along either the upper or lower bound and creating variability much lower than in the non truncation case. But if a random walk path is extremely volatile before truncation, its variability could be still moderately high even after it is cut to the bounds, with the truncated path oscillating between the upper and the lower bound and showing variability comparable to one in the non truncation case. The former case holds for coarse grains and wheat while the latter is deemed to hold for rice. As oscillation between the bounds is not reliable because its variability depends fully on the level of the presumed bounds, the new specification is more desirable despite the fact that its advantage is not explicit in terms of variability.

The relationship of yield variability and price volatility is not as evident for rice as for the other two crops for which higher variability of simulated yields is directly reflected in higher price volatility. As discussed in the previous study, the world rice market is well known for its thinness and frequent government interventions by large exporting countries. The minor contribution of variable yields to rice price volatility underscores the role of unforeseeable policy actions as a significant risk factor to the world rice market.

The proposed new methodology is shown to have superior performance to the previous one for coarse grains and wheat in explaining world price volatility of these commodities. While similar improvement is not achieved for rice in terms of price volatility, it is nevertheless still desirable to apply the new approach because artificial truncation can be avoided. The significance of variable yields in explaining price volatility is reconfirmed by the new methodology as in the previous work. This is especially the case for coarse grains and wheat where contribution of yields to price volatility reaches almost 80%. For rice, risk factors other than yields - presumably policy variables - are suggested to play a much more important role in price volatility.

Experiments and results in this section are all based on the assumption of multivariate normal distribution. There are many other possible specifications for crop yields, although an application of non-normal multivariate distribution for a large number of variables - roughly 100 in this study - becomes extremely complex and computationally intensive when not only variance but also correlations of the variables are to be controlled. While not investigated in this paper, a technical explanation on crop yield distribution is presented at Annex A.1.

2. Price volatility analysis

2.1 Volatile agricultural production in recent years

Agriculture has recently experienced successive and concurring severe shocks, raising concerns about greater uncertainties in agricultural production to a higher profile in the international community. One of the most recent examples is the commodity price spike in 2007-08, triggering higher food prices that generated considerable civil unrest around the world. While a return to more normal harvests in the following years seemed to alleviate much of the concern over commodity shortages, confidence in supplies and the market was hit again in the summer of 2010 when the significant cut in cereal production in countries of the RUK (the Russian Federation, Ukraine and Kazakhstan). These shocks are often a direct consequence of extreme weather events. The more frequent occurrence of these events in recent years has been noted in various editions of the OECD-FAO Agricultural Outlook and by the International Panel on Climate Change (IPCC). Although it is not possible to assert that a similar pattern of volatile production will continue to prevail in the future, it is nevertheless of interest to study the implication of higher yield variability in terms of generating more volatile agricultural markets and to ask to what degree price volatility could be enhanced as a result.

To examine the potential impact of increased yield variability on price volatility, stochastic scenario analyses are undertaken with alternative assumptions. Yields of coarse grains, rice and wheat for some 40 countries[5] are made stochastic by the methodology reviewed in the former section. Multivariate normal distribution is assumed for yield residuals and its variance and covariance are estimated over 1992[6]-2010. In order to see the impacts of changes in randomness, alternative assumptions for yield variability is necessary. For this purpose, the total period 1992-2010 is split into 1992-2000 and 2001-2010 and multivariate yield distribution is estimated over the two distinct sub-periods. In the later section, historical yields are actually shown to be more variable in 2001-2010 than in 1992-2000. Comparisons of the three distinct cases would reveal the implications of not only yield variability but also increases in yield variability. For the sake of expediency, the three scenarios are called Scenario B (base period 1992-2010), Scenario L (low variability 1992-2000) and Scenario H (high variability 2001-10). As the model is designed to simulate market outcomes for 2011-2020, the three scenarios are essentially equivalent to assuming that yield variability for 2011-2020 is to be the observed level in one of the three periods (Table 2.1).

Table 2.1. Three scenarios

	Assumptions of yield variability for 2011-2020	Simulations for 2011-2020
Scenario L	1992-2000 level	Prices 2011-2020, price volatility L
Scenario B	1992-2010 level	Prices 2011-2020, price volatility B
Scenario H	2001-2010 level	Prices 2011-2020, price volatility H

Two aspects of production risk

A second objective of this analysis is to shed light on the market impacts of concurrence of production shocks. As stochastic yields are formulated as log (yield) = trend + residual, the variance of the residual error term has a straightforward relevance; higher variance implies more variable yields. This is important but just one aspect of production risk. Since crop yields in many different regions are examined, correlation between their residuals is also of considerable significance in terms of production risk and price volatility. If there is a large decline in production in one country, this shock could be absorbed or offset through good harvests elsewhere and trade between surplus and deficit regions. However, if a production shortfall is not limited to a specific region and has a rather widespread occurrence across many countries, it is clear that the resulting price surge and volatility could be very high. Depending on the specific crop and importance of the region in question, the impacts of shortfalls on price volatility will likely show considerable variation. For example, a concurrent reduction in

5 The list of the covered countries is presented in Annex A.2.

6 The year 1992 is the oldest year in which data of all the included crops and countries is available in the AGLINK-COSIMO database. This is a constraint necessary for the calculation of the correlation matrix of yield residuals.

production in a number of major exporting countries across diverse regions was identified as one of the factors that triggered the price spike in 2007/08.

As variability of yields is characterised by two components, that is, standard deviation and correlation, it is convenient to define types of risk in terms of its source. Risk represented by standard deviation, or equivalently variance, is called specific risk as an increase or decrease of the standard deviation of a crop yield in one country affects only that specific crop. Correlation between $C_a\_X_i$ and $C_b\_X_j$, where C is a country and X is one of the three grains, is called regional or global depending on whether the two countries are in a given regional group (regional) or cross-regional (global) (Table 2.3). Risk represented by correlation is called regional or global risk as correlation implies that shocks are not limited to a single crop in one country but prevail over different crops and countries or regions. To analyse these two aspects of risk explicitly, price volatility is decomposed into specific risk attribute and non specific risk attribute by comparing simulations with and without correlation.

Table 2.2. Classification of yield shock risks

Multivariate yield distribution	Standard deviations (specific risk)
	Regional correlations (regional risk)
	Global correlations (global risk)

Table 2.3. Regional groups

East Asia	China, Japan, Korea
South East Asia	ASL (Cambodia, Myanmar and others), Indonesia, the Philippines, Malaysia, Thailand, Viet Nam)
South Asia	Bangladesh, India, Pakistan
West Asia	Iran, Turkey
Europe	E15, E12, EUE(other eastern European countries)
RUK	Russian Federation, Ukraine, Kazakhstan
North America	United States, Canada, Mexico
South America	Argentina, Brazil, Chile, Colombia, Peru, Paraguay, Uruguay, SAC(aggregation of Other South American and Caribbean countries)
Oceania	Australia, New Zealand
MLE	Algeria, Egypt, MLE (aggregation of other Middle East countries)
Sub-Saharan Africa	Ghana, Mozambique, Nigeria, Sudan, Tanzania, South Africa

2.2 Estimated standard deviation and correlation coefficients

In line with the three scenarios (Table 2.1), yield variability is calculated for 1992-2010, 1992-2000 and 2001-10, and stochastic yields are generated by random draws from a multivariate normal distribution which has the calculated variance and covariance. Before implementing simulations, it is useful to overlook the standard deviations and correlation coefficients to be used because all the implications of risk in experiments are essentially subsumed in the two statistics.

Standard deviation

A broad picture of the standard deviation or variability of yields is given by Table 2.4 and Figure 2.1. In the formula log(yield) = trend + residual, the value of residuals can be intuitively interpreted; a residual value 0.05 in a specific year implies that the yield recorded 5% higher than its trend level in that year. As such, standard deviation of the residuals measures yield variability in terms of deviation from trend on average. Since standard deviation has the same unit as its data, its value 0.15 can also be read as a 15% deviation from trend on average. Rice yields are shown to be less variable than coarse grains and wheat on average. A high standard deviation is found in RUK (encompassing the Russian Federation, Ukraine and Kazakhstan), Oceania and Sub-Saharan Africa. Two of the largest grain supply regions, *i.e.* North America and Europe, stand in the middle. Low standard deviation in Asian countries could be a reflection of low rice yield variability and any underestimation arising from aggregation. National aggregation underestimates yield variability at the local level by averaging out 1) the huge area of total farmland and its distribution over geographically heterogeneous regions, 2) a variety of different types of farmers from large scale commercial farmers to small subsistence farmers and 3) dry season harvest and wet season double crop harvests. All these characteristics are found in almost all the large Asian rice producing countries. Low variability in these groups needs to be interpreted with caution as it does imply less variation in aggregated national production but does not reflect variation in different producing areas in one country and hence does not necessarily affirm a more stable production environment in those areas. Since the AGLINK-COSIMO model is built on national level databases, this question is not addressed in this work.

Regional correlation

To illustrate the geographical distribution of the regional correlation of yield residuals, the quadratic mean (the root mean square) of correlation coefficients is calculated within a regional group (Table 2.5, Figure 2.2). For example, the quadratic mean value of correlation coefficients between crops within RUK in Scenario L is 0.57 as presented in Table 2.5. As correlation coefficients are between -1 and 1, the value implies a relatively strong tendency between crop yields within the group to move in the same direction. Strong correlation is found in North America, Europe, Oceania and the RUK, where a shock to one crop is reasonably deemed to be a shock to other crops in crop rotation within that region, suggesting high correlation between them. Water scarce countries also show strong correlation (West Asia, Oceania and the Middle East) as the disruption of water supply would affect total agricultural production regardless of crop specificities, suggesting high correlation between different crops in the region. The detailed information is given in Annex A.3. A warning is made for potential overestimation of regional correlation risk by disaggregation of crops. Coarse grains such as barley, maize and rye are treated individually in many crop rotation countries whereas in other countries these grains are often aggregated in one item “coarse grains”. The latter is the case, for example, for the Indian module, where non negligible production is recorded for barley, maize, millet and sorghum while correlation coefficients between these grains cannot be taken into account due to the aggregation. The root mean square of regional correlations in South Asia would be much higher, for example, if the absent correlation coefficients, presumably high, were accounted for. Whereas a comparison of correlation risk within one region between different scenarios is possible, the variation in averaged correlation over different regions should not be interpreted as a precise reflection of the relative risk of different regions. Relatively high correlations found in crop rotation regions should not be interpreted to imply higher risk in those regions than in other regions.

Global correlation

Among roughly 4 500 correlation coefficients of pairs of crops that belong to different regions, only 4.3% of them are found to be significantly different from zero. As the implication of impacts becomes obscure if all of the 4 500 correlation coefficients are taken into account, the focus is placed on statistically significant relationships between large producing and exporting regions. Within this limited scope, a strong link is found between Europe and RUK, and between Oceania and North America (Annex A.5) in 2001-10. Ukraine is found to be correlated not only with the Russian Federation but also with Europe, reflecting its geographical location. A statistically significant link is found between Australia and the North America. Although counter-intuitive from the geographical viewpoint, the positive correlation coefficients between Australia and the North America in 2001-10 are a reflection of extreme weather events that hit these countries concurrently in 2002, 2006 and 2007. These correlations between $C_a\_X_i$ and $C_b\_X_j$ where (C_a, C_b) is either (RUK, Europe) or (Oceania, North America) are taken into account as global correlation risk.

Higher variability scenario reflected in standard deviation and correlation

As expected, Scenario H (2001-2010) was found to present higher yield variability both in standard deviation and correlation coefficients (Figures 2.1 and 2.2). Seven out of eleven regions show an increase in standard deviation in the high risk scenario compared to Scenario L (1992-2000), with strong increases found in West Asia and Europe, and most notably in Oceania, where successive large failures of harvests have been recorded in the last ten years reflecting climatic events associated with the *El Nino* phenomenon. Although both increases and decreases are found in correlations depending on regions, the most notable is the strong increase in major cereal suppliers, i.e. Europe and North America. Thus Scenario H (stochastic yields estimated over 2001-10) is characterised relative to Scenario L (1992-2000) as a scenario of higher standard deviation in general and higher correlation in some important grain exporting regions.

Table 2.4. Average of standard deviation of yields by crops and regions

	Scenario L 1992-2000	Scenario B 1992-2010	Scenario H 2001-2010
East Asia	7.0%	6.5%	5.5%
South East Asia	3.5%	4.3%	3.9%
South Asia	5.1%	5.9%	5.7%
West Asia	7.2%	10.0%	10.9%
Europe	8.4%	9.8%	10.9%
RUK	17.8%	18.2%	18.4%
North America	7.3%	8.3%	8.5%
South America	9.2%	9.8%	8.9%
Oceania	11.0%	17.9%	20.5%
MLE	13.3%	12.7%	11.3%
Sub-Saharan Africa	18.7%	17.9%	15.7%

Figure 2.1. Average of standard deviation of yields by regions

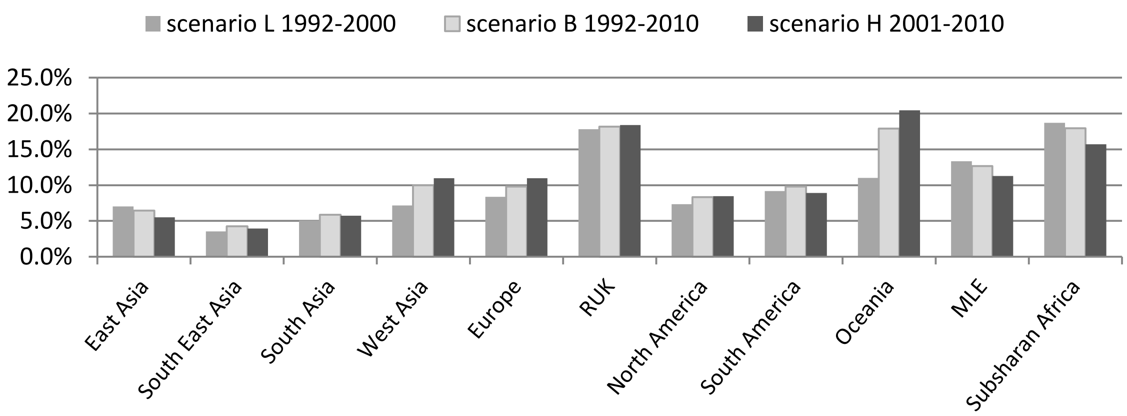
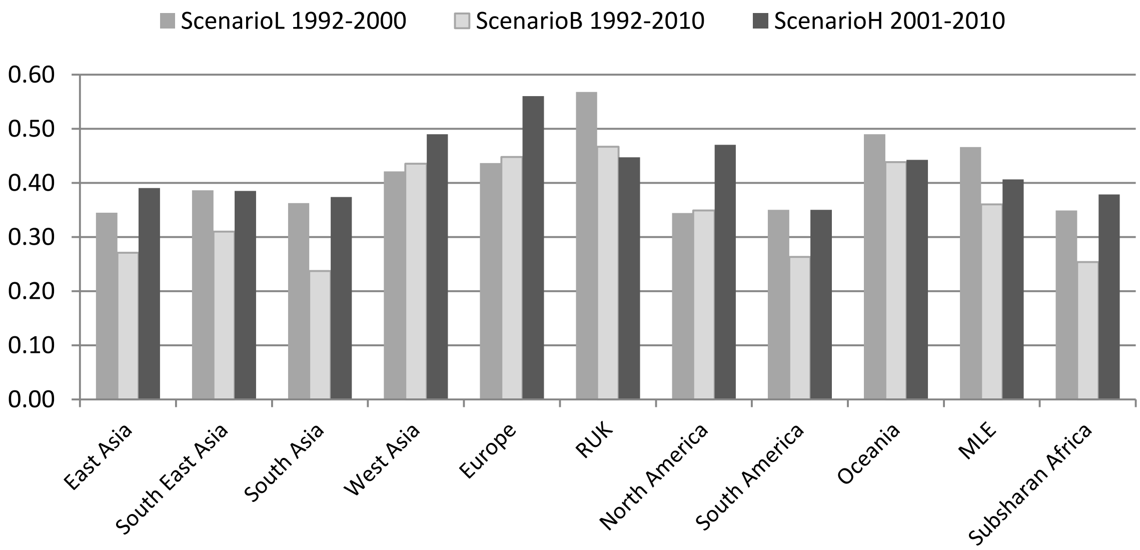


Table 2.5. Quadratic mean of correlation coefficients of yield residuals by regions

	Scenario L 1992-2000	Scenario B 1992-2010	Scenario H 2001-2010
East Asia	0.34	0.27--	0.39
South East Asia	0.39	0.31	0.39
South Asia	0.36	0.24	0.37
West Asia	0.42	0.44	0.49
Europe	0.44	0.45	0.56
RUK	0.57	0.47	0.45
North America	0.34	0.35	0.47
South America	0.35	0.26	0.35
Oceania	0.49	0.44	0.44
MLE	0.47	0.36	0.41
Sub-Saharan Africa	0.35	0.25	0.38

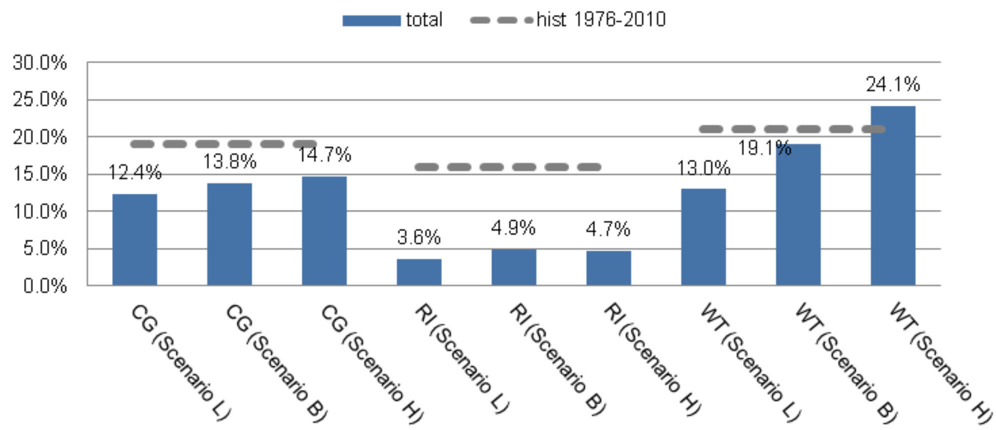
Figure 2.2. Quadratic mean of correlation coefficients of yield residuals by regions



2.3 Stochastic simulations based on 1992-2000 and 2001-2010

The results of stochastic simulations for the three scenarios are summarised in Figure 2.3. Price volatility is measured by standard deviation of seven observations of annual changes over 2014-20[7]. For example, a value of 10% in this measurement means that year-to-year changes of prices tend to be 10% on average over 2014 to 2020. Scenario H generates higher price volatility than Scenario L for three crops, with a remarkably strong increase for wheat - almost 1.9 times - while it is modest for coarse grains and rice. The implication of whether the future yield variability will follow the high risk pattern observed in 2001-10 or the low risk pattern observed in 1992-2000 or somewhere in between has a profound significance, especially for wheat, as the high risk scenario implies almost 85% higher price volatility than in the low risk case, possibly exceeding the historical level.

Figure 2.3. Simulated price volatility by three scenarios



Decomposition of price volatility

Simulations are executed under three assumptions; 1) no correlation between crops within and between regions, 2) correlation allowed for within a regional group, and 3) correlation allowed for within a regional group and between large producing and exporting regions (Table 2.6). By identifying differences between the three assumptions, price volatility is decomposed into three portions; contribution of specific risk, regional correlation risk, and global correlation risk (Table 2.7 and Figures 2.4 and 2.5). Contribution of correlation risk is shown to be significant especially in Scenario H for coarse grains and wheat, with roughly 40% to 45% of the total volatility being attributable to it. Variation in individual crops is dominant in generating price volatility as specific crop risk explains a large portion of this volatility. The role of correlation was discussed earlier and its impact is numerically made explicit here by the simulations. The results suggest that neglect of the correlation effect can result in a serious underestimation of risk. The source of price volatility is not limited to the magnitude of yield shocks per se, but also their geographical scope; that is, whether shocks have a tendency to affect crops in different countries and regions concurrently or not (i.e. and thereby have a large effect on global production).

7 See Footnote 3 for the definition of price volatility.

Table 2.6. Price volatility by different correlation assumptions

Scenario L (1992-2000)			
	1/ No correlation	**2/ Regional correlation**	**3/ Regional and global correlation**
CG	12.5%	13.3%	12.4%
RI	3.3%	3.5%	3.6%
WT	12.3%	15.0%	13.0%
Scenario H (2001-2010)			
	1/ No correlation	**2/ Regional correlation**	**3/ Regional and global correlation**
CG	8.9%	12.6%	14.7%
RI	4.0%	4.9%	4.7%
WT	13.1%	19.6%	24.1%

Figure 2.4. Example of decomposition: wheat price volatility in Scenario H

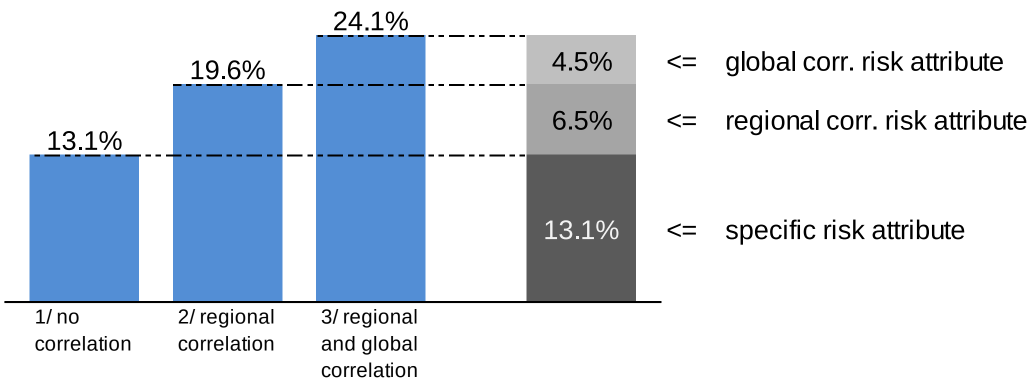
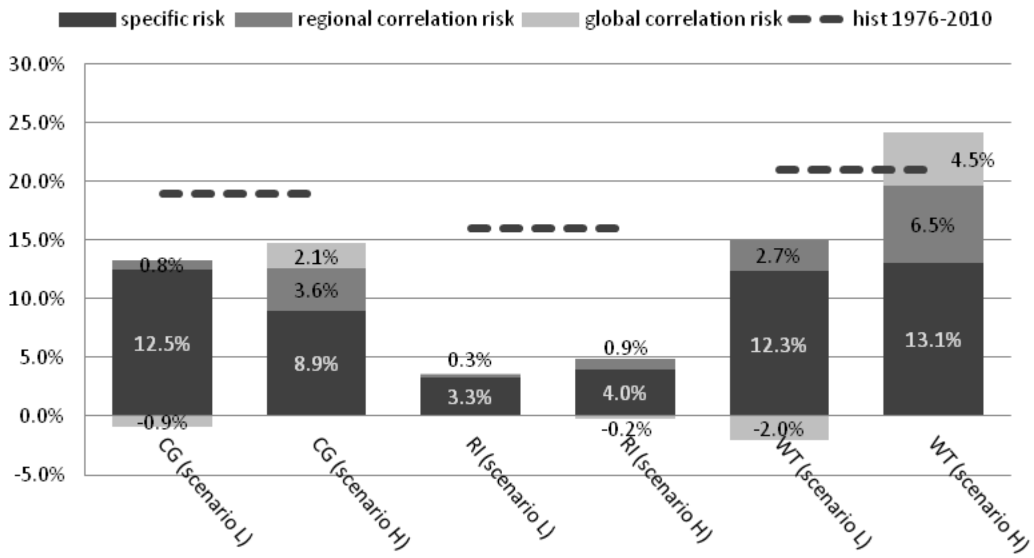


Table 2.7. Decomposition of price volatility into different risk attributes

Scenario L (1992-2000)				
	Specific risk attribute	**Regional correlation risk attribute**	**Global correlation risk attribute**	**Total**
CG	12.5%	0.8%	-0.9%	12.4%
RI	3.3%	0.3%	0.1%	3.6%
WT	12.3%	2.7%	-2.0%	13.0%
Scenario H (2001-2010)				
	Specific risk attribute	**Regional correlation risk attribute**	**Global correlation risk attribute**	**Total**
CG	8.9%	3.6%	2.1%	14.7%
RI	4.0%	0.9%	-0.2%	4.7%
WT	13.1%	6.5%	4.5%	24.1%

Figure 2.5. Decomposition of price volatility into different risk attributes



Comparison of the results of two scenarios

With the decomposition of price volatility, it is possible to analyse the implication of the high risk and low risk scenarios in more detail than looking at merely changes in total volatility. Higher total price volatility for coarse grains and wheat in Scenario H is revealed to be attributable almost exclusively to higher regional and global correlation risk. On the other hand, the contribution of specific risk of yield variation in raising price volatility in Scenario H is much smaller, or negative, when compared to regional and global correlation risk. Price volatility is higher in Scenario H not because individual crop yields are more variable but because they are more correlated.

Regional and global correlation plays a smaller role in coarse grains than in wheat, most typically in Scenario L, where correlation contribution is marginal in coarse grains. As the United States has a dominant position both in production and exports of coarse grains, and particularly maize, shocks specific to the crop in that country may have a larger significance than in the case of wheat, and explaining the smaller contribution of correlation in coarse grains price volatility. For example, as opposed to higher yield variability in many regions in Scenario H, variability of USA maize yields is actually much lower in 2001-10 (4.8%) than in 1992-2000 (9.2%) (Annex A.2). This would be one of the factors explaining a lower contribution of specific risk to coarse grains price volatility in Scenario H. As world wheat production is more regionally diverse with large shares of production and exports held by several countries located mainly in the temperate zone, the tendency of a coincidence of shocks in different countries would play a more critical role in wheat price volatility, which is well reflected in a larger contribution of correlation risk in wheat than in coarse grains. A considerable increase in the correlation component in wheat price volatility in Scenario H is deemed to be a reflection of 1) higher regional correlation within Europe, 2) higher regional correlation within North America, 3) global correlation between RUK and Europe, and finally, 4) global correlation between Oceania and North America.

The revealed role of global correlation sheds light on an aspect of risk mitigation. Global correlation functions as risk diversification in Scenario L, lowering price volatility, although to a small degree, whereas it switches to be a risk intensifying factor in Scenario H. Correlation coefficients between RUK and Europe, and Oceania and North America (Annex A5) is often close to zero or even negative in 1992-2000 (Scenario L period) while many of them turn to be significantly positive and well above 0.70 in 2001-10, (Scenario H period) which implies very high correlation. Here the role of correlation is clearly articulated; diversification of supply sources can reduce price volatility if their exposure to risk of concurrent shocks is very limited, while this mitigating effect is absent when faced with the risk represented by positive correlation.

Simulations are again not successful with regard to rice as demonstrated in the first part of this paper, and a detailed analysis is not permitted by the decomposition analysis as only very small changes are observed. One noticeable thing is again a low standard deviation or yield variation for rice. The trade shares of Thailand and Viet Nam account for almost half of the world total exports. This concentration of trade in two countries would suggest that their standard deviation and correlation should have a considerable effect. Given standard deviation values for yield variation of only 4.5% and 2.9% for rice in the two countries, respectively (Annex A.3), the standard deviation of the aggregated production variation of the two countries, which account for almost 50% of world rice exports, is a maximum of 4.5% as it is a weighted average of the two, well below the level of the other two crops of wheat and coarse grains (Table 2.4). Although a low standard deviation of yield variation in national production does not necessarily mean a more stable production environment as already discussed, the model based on national level data is not capable of further analysis and decomposition of rice price volatility.

2.4 Conclusions and further steps

Most agriculture outlook work by various agencies now incorporates stochastic analysis. A number of member countries have expressed an interest in such analysis as a means to better understand the uncertainties around medium-term market projections, to increase the knowledge about the drivers of market volatility and to undertake more sophisticated scenario analyses. There is a need to develop the analytical tools and the ways of interpreting and presenting the results. This note is one of a series of Secretariat contributions to this process. The European Commission, for example, is developing its own capacity in this area using the AGLINK-COSIMO model and the sharing of experiences with the Secretariat has benefited both parties.

While the methodologies used, and statistical results presented, are quite technical, the benefits of this work are clear. The new methodologies provide a less restrictive way of representing yield volatility and, as such, do a better job of accounting for the impact on price volatility. In addition, the greater regional disaggregation allows the analysis of more homogenous production regions and greater regional specificity. Increasing the random draws from 150 to 500 provides more robust results for the scenario analyses.

The decomposition of sources of yield variability into shocks to specific crops (specific risk), shocks across crops within a country/region (regional correlation) and shocks across crops on a global scale (global correlation) adds new insight into these different components of yield variability. The value added of this work is to provide some quantitative measures of the impacts of these various sources of yield variability on price volatility. The specific risk contribution has a larger impact on price volatility for coarse grains while the reverse is true for wheat. This contrast is a reflection of the difference in geographical distribution and country concentration of production and supply of these two crops. For rice, the contribution of regional and global correlation to price volatility was much less than specific risk.

High and low risk scenarios, which correspond to yield variability and correlation based on the 1992-2000 and 2001-2010 periods, are simulated. The yield shocks in the higher risk scenario generated 30% higher price volatility (compared with the low risk scenario) for coarse grains and 80% for wheat. The difference between scenarios for rice was negligible. Higher volatility is attributable almost solely to a higher correlation rather than standard deviation in the high risk scenario, which confirms the significance of concurrent shocks to different crops and countries that result in large price variation.

While an external aspect of risk, especially yield shocks, has been studied in this series of stochastic analyses exploiting the AGLINK-COSIMO model, another aspect of risk, i.e. responses of consumers and producers to the shocks is not addressed. As economic agents' behaviours would differ depending on the nature of risk, their degree of risk aversion, and risk hedging tools available to them, the results of the studies could show a non negligible variation according to the assumptions of those factors. A perception by farmers of higher risk in a particular crop may prompt shifts to other crops, gradually effecting production patterns. The lack of the consideration of a dynamic supply and demand response is a limitation of the current model and study and an area for possible future work.

Another area for further research could be to examine structural changes in yield variance and covariance, such as an adaptation of new varieties or technologies, longer term fluctuations in climate, or changes in dependency on irrigation. Such analysis would help explain observed differences in variance and covariance across crops, between regions and over time. This study is based on the application of a specific formula for identifying yield variation [log(yield) = trend + residual with the assumption of normal distribution for residual]. Autoregressive and moving average processes can better reflect an impact of past shocks on the harvest of the present year. This capacity is relevant when the persistence of shocks is to be considered. Shocks such as water shortage or drought could be so severe that its damage could continue to prevail into the next year or beyond for perennial agricultural crop production (e.g. sugarcane ratoons, replacement of old grape vines and fruit trees).

Whereas in this study the emphasis has been placed on the impacts on price volatility, it would be interesting especially in the context of risk analysis and food security, to focus on the impact on the volatility in other variables such as trade volumes, area harvested, stock levels, and last but not least, consumption. High volatility in consumption could imply increased food security risk. Examining the volatility of other variables would shed light on such market responses as supply response from domestic production, more frequent trade or flexible supply from stocks, which is of considerable importance with respect to the assessment of vulnerability of a country.

The assumption of a normal distribution can underestimate downward production shocks. In agriculture, large shocks to crops are typically ones that lower production as a halving of production is not uncommon while a doubling would be very rare except in cases of recovery of low production to normal levels. The estimation based on applying a normal distribution treats all those shocks as being symmetrical - it considers only the absolute magnitude of recorded shocks and not whether they are positive or negative. To remedy this potential underestimation of downward shocks, an extreme value approach can be tested to remove extremely low values from normal fluctuations. With this approach, yield variability and resulting price volatility could be decomposed into two components, one attributable to normal shocks and the other attributable to extreme shocks. With the identification of extreme shocks, even by a primitive method, the data can be combined with information on the background of the shocks, such as extreme weather events related to *El Niño* or high temperature that prevailed in a region. A collection of historical information which identifies 1) in which crop, in which country and in which year an extreme weather event or an extreme shock was recorded, 2) and their causes, can provide a very useful survey of the frequency of extreme events, or its temporal and geographical distribution. This issue has been a central issue in discussions of agricultural productions and markets in the recent years.

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Annex

A.1 Alternative approaches to the analysis of crop yield distribution

Probability distribution of crop yields has drawn the attention of researchers and policy makers and the academic literature is rich in this area. Much of the research is from the perspective of crop insurance and related policies (Goodwin and Ker, 1998; Sherrick *et al.*, 2004; Cooper, 2010). In this context, precision of estimates is the central issue because examination of the actuarial soundness of insurance schemes is critically conditional upon the quantitative assessment of crop failure risk. These studies explore statistically sophisticated methodologies such as nonparametric kernel density estimates, bootstrap and copulas in order to obtain an optimal approach for estimating probability densities of crop losses.

Another approach is to undertake stochastic simulations using large economic simulation models. FAPRI (Food and Agricultural Policy Research Institute) (2006), Meyer *et al.* (2010), EC (the European Commission) (2012) and OECD (2011) belong to this category. One of the advantages of large sectoral models such as the OECD AGLINK-COSIMO and FAPRI model is the capacity to simulate comprehensive market mechanism by equilibrating many different commodity and country markets simultaneously by linking them together through global market clearing. Whereas these stochastic studies do attempt to introduce a large number of random variables to analyse overall impacts of uncertainty on markets, particularly in contrast to non stochastic simulations, they do not pursue the exact distributions specific to each variable.

Given the clear trade-off between the coverage of stochastic factors and the precision of estimates, a single formula (multivariate empirical or multivariate normal distribution) is applied uniformly to many different random variables in these stochastic experiments. As this study also attempts to randomize some 100 crop yields over 40 countries, a unique formula – multivariate normal – is chosen for the generation of stochastic yields. The role of variance and covariance is highlighted in the second part of this study, and multivariate normal distribution serves this objective because of its capacity to replicate designated values for standard deviations and correlation coefficients.[8]

Clearly, the choice of one functional form for yield distribution does not deny the possibility of alternative formulae. While stationarity is required for the application of normality, non-stationarity is not rejected for 17% of the treated yield residuals by the augmented Dickey-Fuller test. The application of ARMA (autoregressive moving average process)[9] could improve the goodness-of-fit, although not pursued for in this study.

Another aspect of choice of yield specification is to introduce endogenous crop yields, where yields are function of prices so that production adjustment is possible not only in area planted to crops but also in yields. Endogenised yields would better reflect farmers' responses to shocks and

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8 Departing from normality, it is not impossible to enforce a particular correlation/dependence structure on a multivariate distribution. Liu *et al.* (2011) exploits the copula approach for a multivariate distribution for wheat production of eight countries with heterogeneous marginal distributions (normal, Weibul and logistic). The technical and computational burden is huge, especially if the number of variables becomes larger.

9 An application of ARMA makes the interpretation of the role of correlation of residuals difficult. An ARMA process varies due not only to errors but also to its deterministic cycles. A positive correlation between residuals of two ARMA processes does not necessarily imply a tendency of the two series to move together, because the contribution to fluctuations of deterministic cycles, which may or may not covary, can exceed that of residuals.

are particularly important when the target of study is to analyse their behaviour and its impact on markets.

A2. Abbreviations

Crops

cg	Coarse grains
ba	Barley
ma	Maize
ry	Rye
ri	Rice
wt	Wheat
wtd	Wheat, durum
wts	Wheat, soft

Countries

chn	China
jpn	Japan
kor	Korea
e12	EU12
e15	EU15
kaz	Kazakhstan
rus	Russian Federation
ukr	Ukraine
eue	Other eastern European countries
dza	Algeria
egy	Egypt
mle	Middle East countries
can	Canada
mex	Mexico
usa	United States
aus	Australia
nzl	New Zealand
gha	Ghana
moz	Mozambique
nga	Nigeria
sdn	Sudan
tza	Tanzania
zaf	South Africa
arg	Argentina
bra	Brazil
chl	Chile
col	Colombia
per	Peru
pry	Paraguay
sac	Other South American and Caribbean countries
ury	Uruguay
bgd	Bangladesh
ind	India
pak	Pakistan
asl	Asian LDCs (Cambodia, Myanmar and others)
idn	Indonesia
mys	Malaysia
phl	Philippines
tha	Thailand
vnm	Viet Nam
irn	Iran
tur	Turkey

A3. Standard deviation of yield residuals calculated over 1992-2000 and 2001-2010

		Scenario L 1992-2000	Scenario H 2001-2010			Scenario L 1992-2000	Scenario H 2001-2010
Europe	e12_ba	5.6%	9.9%	North America	can_ba	4.7%	11.2%
	e12_ma	21.1%	20.4%		can_ma	9.9%	7.8%
	e12_ry	8.2%	9.2%		can_wt	5.4%	13.3%
	e12_wtd	5.1%	17.7%		mex_ba	17.3%	15.4%
	e12_wts	5.9%	12.6%		mex_ma	6.3%	5.3%
	e15_ba	6.3%	4.6%		mex_ri	7.3%	9.3%
	e15_ma	5.1%	6.0%		mex_wt	7.0%	5.4%
	e15_ri	5.2%	2.6%		usa_ba	4.1%	9.9%
	e15_ry	10.2%	12.3%		usa_ma	9.2%	4.8%
	e15_wtd	10.6%	11.0%		usa_ri	3.7%	3.5%
	e15_wts	4.7%	5.0%		usa_wt	5.6%	7.1%
	eue_cg	9.9%	14.1%		average	7.3%	8.5%
	eue_wt	10.7%	17.0%				
	average	8.4%	10.9%	South America	arg_ba	14.5%	18.0%
					arg_ma	9.2%	7.7%
RUK	kaz_cg	29.1%	18.4%		arg_ri	8.6%	6.4%
	kaz_wt	25.6%	20.2%		arg_wt	8.6%	15.3%
	rus_ba	20.3%	15.4%		bra_ma	9.1%	8.2%
	rus_ma	24.2%	32.4%		bra_ri	5.6%	4.3%
	rus_ri	6.8%	8.1%		bra_wt	11.9%	16.2%
	rus_ry	19.3%	17.4%		chl_cg	12.9%	7.9%
	rus_wt	14.2%	12.5%		chl_wt	5.9%	11.0%
	ukr_cg	8.6%	14.5%		col_ri	9.8%	3.8%
	ukr_wt	12.0%	26.7%		per_cg	6.1%	3.0%
	average	17.8%	18.4%		per_ri	4.3%	3.6%
					pry_cg	13.9%	11.1%
Oceania	aus_ba	15.9%	30.7%		sac_cg	4.2%	4.5%
	aus_ri	7.5%	12.1%		sac_ri	1.8%	2.0%
	aus_wt	17.4%	33.0%		sac_wt	9.2%	6.0%
	nzl_cg	3.2%	6.0%		ury_cg	13.5%	8.2%
	average	11.0%	20.5%		ury_ri	9.4%	7.4%
					ury_wt	17.7%	30.6%
					average	9.3%	9.2%

		Scenario L 1992-2000	Scenario H 2001-2010			Scenario L 1992-2000	Scenario H 2001-2010
East Asia	chn_ma	7.0%	3.0%	Middle East	dza_cg	26.7%	14.6%
	chn_ri	1.2%	1.3%		dza_wt	17.0%	13.3%
	chn_wt	3.7%	2.8%		egy_cg	6.0%	2.5%
	jpn_ri	11.3%	4.0%		egy_ri	2.3%	2.4%
	jpn_wt	8.7%	15.7%		egy_wt	3.4%	1.4%
	kor_cg	11.6%	6.3%		mle_cg	26.0%	25.5%
	kor_ri	5.5%	5.3%		mle_wt	12.0%	19.2%
	average	7.0%	5.5%		average	13.3%	11.3%
South East Asia	asl_ri	2.3%	2.4%	Subsaharan Africa	gha_cg	8.2%	13.8%
	idn_cg	3.2%	2.4%		gha_ri	13.9%	6.9%
	idn_ri	5.6%	3.0%		moz_ri	35.9%	10.4%
	mys_ri	5.1%	3.3%		nga_ri	9.6%	17.1%
	phl_cg	3.6%	6.2%		sdn_cg	14.9%	29.6%
	phl_ri	3.6%	3.7%		sdn_wt	26.8%	19.7%
	tha_cg	5.7%	2.0%		tza_cg	13.0%	17.9%
	tha_ri	2.7%	4.5%		tza_ri	13.5%	17.1%
	vnm_ri	0.6%	2.9%		zaf_cg	35.3%	12.5%
	average	3.6%	3.4%		zaf_wt	15.9%	11.9%
					average	18.7%	15.7%
South Asia	bgd_ri	5.6%	1.5%				
	ind_cg	7.4%	7.7%				
	ind_ri	3.2%	5.2%				
	ind_wt	3.3%	4.0%				
	pak_ri	6.2%	11.9%				
	pak_wt	4.7%	4.0%				
	average	5.1%	5.7%				
West Asia	irn_cg	8.6%	25.9%				
	irn_ri	6.7%	7.1%				
	irn_wt	7.8%	13.4%				
	tur_cg	4.3%	8.0%				
	tur_ri	8.9%	5.7%				
	tur_wt	6.7%	5.6%				
	average	7.2%	10.9%				

A4. Regional correlation coefficients of yield residuals calculated over 1992-2001 and 2001-2010

An asterisk is given to significance of 5%.

East Asia

scenario L 1992-2000							
	chn_ma	chn_ri	chn_wt	jpn_ri	jpn_wt	kor_cg	kor_ri
chn_ma	1						
chn_ri	-0.17	1					
chn_wt	-0.57	0.31	1				
jpn_ri	-0.44	0.32	-0.16	1			
jpn_wt	-0.23	0.03	0.06	-0.09	1		
kor_cg	0.17	-0.5	0.15	0.01	-0.37	1	
kor_ri	-0.62	0.46	0.46	0.65	-0.05	0.02	1

scenario H 2001-2010							
	chn_ma	chn_ri	chn_wt	jpn_ri	jpn_wt	kor_cg	kor_ri
chn_ma	1						
chn_ri	-0.06	1					
chn_wt	0.58	-0.02	1				
jpn_ri	0.42	**0.64***	0.14	1			
jpn_wt	0.59	-0.4	0.44	0.11	1		
kor_cg	0.3	0.19	0.03	0.47	0.07	1	
kor_ri	0.26	0.56	0.31	**0.66***	-0.11	0.53	1

South East Asia

scenario L 1992-2000									
	asl_ri	idn_cg	idn_ri	mys_ri	phl_cg	phl_ri	tha_cg	tha_ri	vnm_ri
asl_ri	1								
idn_cg	-0.48	1							
idn_ri	0.11	-0.33	1						
mys_ri	-0.19	-0.38	0.02	1					
phl_cg	0.33	-0.63	0.3	0.48	1				
phl_ri	-0.04	-0.37	0.66	0.46	0.15	1			
tha_cg	-0.15	0.24	-0.31	0.21	-0.59	-0.02	1		
tha_ri	0.48	-0.47	-0.25	0.35	0.04	0	0.46	1	
vnm_ri	0.53	**-0.72***	0.02	0.49	**0.73***	0.07	-0.26	0.39	1

scenario H 2001-2010									
	asl_ri	idn_cg	idn_ri	mys_ri	phl_cg	phl_ri	tha_cg	tha_ri	vnm_ri
asl_ri	1								
idn_cg	-0.4	1							
idn_ri	0.09	0.22	1						
mys_ri	0.2	0.5	**0.64***	1					
phl_cg	**0.82***	-0.29	0.09	0.12	1				
phl_ri	0.51	-0.6	0.02	-0.21	0.43	1			
tha_cg	-0.08	0.57	-0.27	0.08	0.16	**-0.68***	1		
tha_ri	0.07	-0.24	-0.16	-0.19	0.11	**0.69***	-0.37	1	
vnm_ri	-0.53	0.18	-0.08	-0.24	-0.34	0.27	-0.27	**0.70***	1

South Asia

scenario L 1992-2000						
	bgd_ri	ind_cg	ind_ri	ind_wt	pak_ri	pak_wt
bgd_ri	1					
ind_cg	0.2	1				
ind_ri	-0.25	0.06	1			
ind_wt	0	-0.15	-0.63	1		
pak_ri	0.24	-0.44	-0.22	-0.1	1	
pak_wt	**0.68***	0.01	**-0.76***	0.29	0.18	1

scenario H 2001-2010						
	bgd_ri	ind_cg	ind_ri	ind_wt	pak_ri	pak_wt
bgd_ri	1					
ind_cg	0.23	1				
ind_ri	0.2	**0.74***	1			
ind_wt	-0.08	-0.54	-0.35	1		
pak_ri	**0.72***	-0.15	-0.1	-0.08	1	
pak_wt	0.45	0.16	0.41	0	0.29	1

West Asia

scenario L 1992-2000						
	irn_cg	irn_ri	irn_wt	tur_cg	tur_ri	tur_wt
irn_cg	1					
irn_ri	0.36	1				
irn_wt	0.19	0.61	1			
tur_cg	-0.35	0.28	0.22	1		
tur_ri	-0.42	-0.29	-0.53	0.25	1	
tur_wt	-0.54	-0.2	-0.19	**0.81***	0.5	1

scenario H 2001-2010						
	irn_cg	irn_ri	irn_wt	tur_cg	tur_ri	tur_wt
irn_cg	1					
irn_ri	0.56	1				
irn_wt	**0.77***	0.48	1			
tur_cg	0.42	0.24	**0.69***	1		
tur_ri	-0.4	**-0.74***	-0.28	0.06	1	
tur_wt	-0.02	-0.18	0.47	**0.75***	0.39	1

Europe

scenario L 1992-2000	e12_ba	e12_ma	e12_ry	e12_wtd	e12_wts	e15_ba	e15_ma	e15_ri	e15_ry	e15_wtd	e15_wts	eue_cg	eue_wt
e12_ba	1												
e12_ma	**0.90***	1											
e12_ry	**0.86***	**0.76***	1										
e12_wtd	-0.12	-0.17	-0.1	1									
e12_wts	**0.67***	0.56	0.58	0.19	1								
e15_ba	-0.08	-0.09	-0.07	-0.27	-0.54	1							
e15_ma	0.12	0.16	-0.05	0.05	-0.14	**0.75***	1						
e15_ri	0.34	0.44	0.18	0.43	0.14	0.39	**0.78***	1					
e15_ry	0.47	0.51	0.51	-0.34	0.26	0.58	0.6	0.42	1				
e15_wtd	-0.33	-0.42	-0.3	0.49	-0.31	-0.13	-0.4	-0.14	-0.61	1			
e15_wts	0.03	0.01	0.16	-0.1	-0.29	**0.88***	0.6	0.4	**0.71***	0	1		
eue_cg	**0.83***	**0.84***	**0.68***	-0.19	0.47	-0.33	-0.06	0.19	0.11	-0.39	-0.38	1	
eue_wt	0.37	0.13	0.25	-0.21	0.41	-0.51	-0.46	-0.33	-0.35	-0.02	-0.59	0.48	1

scenario H 2001-2010	e12_ba	e12_ma	e12_ry	e12_wtd	e12_wts	e15_ba	e15_ma	e15_ri	e15_ry	e15_wtd	e15_wts	eue_cg	eue_wt
e12_ba	1												
e12_ma	0.45	1											
e12_ry	**0.83***	0.29	1										
e12_wtd	0.49	**0.71***	0.25	1									
e12_wts	**0.89***	**0.72***	**0.70***	**0.75***	1								
e15_ba	**0.66***	0.11	**0.65***	0.04	0.5	1							
e15_ma	**0.64***	0.08	**0.63***	0.59	0.62	0.47	1						
e15_ri	0.25	0.05	0.3	-0.14	0.12	0.41	0.02	1					
e15_ry	**0.77***	0.6	**0.64***	0.61	**0.79***	0.58	0.56	0.27	1				
e15_wtd	0.46	0.17	0.21	0.4	0.43	0.38	0.42	-0.4	0.12	1			
e15_wts	**0.79***	**0.73***	**0.68***	0.6	**0.83***	**0.66***	0.5	0.34	**0.82***	0.38	1		
eue_cg	0.52	**0.94***	0.37	**0.89***	**0.80***	0.14	0.37	-0.02	**0.65***	0.32	**0.76***	1	
eue_wt	**0.68***	0.48	0.58	**0.77***	**0.80***	0.33	**0.76***	-0.32	0.49	**0.73***	0.59	**0.70***	1

RUK (the Russian Federation, Ukraine, Kazakhstan)

scenario L 1992-2000	kaz_cg	kaz_wt	rus_ba	rus_ma	rus_ri	rus_ry	rus_wt	ukr_cg	ukr_wt
kaz_cg	1								
kaz_wt	**0.88***	1							
rus_ba	**0.71***	0.53	1						
rus_ma	0.27	0.54	0.34	1					
rus_ri	**-0.72***	**-0.67***	-0.08	-0.09	1				
rus_ry	**0.81***	**0.86***	**0.84***	0.6	-0.3	1			
rus_wt	**0.81***	**0.82***	**0.82***	**0.71***	-0.38	**0.92***	1		
ukr_cg	0.29	0.36	0.48	**0.75***	-0.05	0.5	0.64	1	
ukr_wt	-0.28	-0.33	-0.41	0.02	-0.16	-0.52	-0.23	0.38	1

scenario H 2001-2010	kaz_cg	kaz_wt	rus_ba	rus_ma	rus_ri	rus_ry	rus_wt	ukr_cg	ukr_wt
kaz_cg	1								
kaz_wt	**0.84***	1							
rus_ba	0.36	0.34	1						
rus_ma	-0.23	-0.04	0.14	1					
rus_ri	-0.06	0.14	-0.03	-0.12	1				
rus_ry	**0.85***	**0.84***	**0.69***	0.08	-0.02	1			
rus_wt	0.41	0.49	**0.79***	0	0.43	**0.69***	1		
ukr_cg	-0.26	-0.11	0.56	0.28	0.33	0.15	0.56	1	
ukr_wt	-0.16	0.12	0.27	-0.08	**0.73***	0.12	**0.63***	**0.73***	1

North America

scenario L 1992-2000											
	can_ba	can_ma	can_wt	usa_ba	usa_ma	usa_ri	usa_wt	mex_ba	mex_ma	mex_ri	mex_wt
can_ba	1										
can_ma	0.2	1									
can_wt	0.66	0	1								
usa_ba	0.24	-0.6	0.01	1							
usa_ma	-0.45	-0.1	-0.11	0.13	1						
usa_ri	-0.06	-0.51	0.01	0.23	0.5	1					
usa_wt	-0.24	-0.06	-0.01	0.25	0.26	-0.43	1				
mex_ba	0.09	-0.23	0	0.01	0	0.65	-0.42	1			
mex_ma	0.39	-0.26	-0.18	**0.73***	-0.27	0.07	0.02	0.32	1		
mex_ri	0.62	0.02	0.05	0.46	-0.53	-0.02	-0.37	-0.01	0.21	1	
mex_wt	-0.4	-0.32	-0.05	-0.24	0.24	0.24	0.4	0.22	0.02	**-0.51***	1

scenario H 2001-2010											
	can_ba	can_ma	can_wt	usa_ba	usa_ma	usa_ri	usa_wt	mex_ba	mex_ma	mex_ri	mex_wt
can_ba	1										
can_ma	**0.68***	1									
can_wt	**0.95***	**0.83***	1								
usa_ba	**0.68***	0.29	0.6	1							
usa_ma	**0.68***	0.12	0.51	0.55	1						
usa_ri	-0.26	-0.48	-0.38	-0.34	0.46	1					
usa_wt	**0.72***	0.44	0.59	0.61	0.48	-0.31	1				
mex_ba	-0.22	-0.37	-0.33	-0.18	0.19	0.59	-0.16	1			
mex_ma	-0.04	-0.22	-0.08	-0.48	0.2	0.62	-0.3	0.37	1		
mex_ri	0.3	0.05	0.33	**0.71***	0.22	-0.29	0.25	-0.12	-0.34	1	
mex_wt	**-0.64***	-0.51	-0.56	**-0.68***	-0.52	0.22	**-0.89***	0.16	0.48	-0.37	1

South America

scenario L 1992-2000	arg_ba	arg_ma	arg_ri	arg_wt	bra_ma	bra_ri	bra_wt	chl_cg	chl_wt	col_ri	per_cg	per_ri	pry_cg	sac_cg	sac_ri	sac_wt	ury_cg	ury_ri	ury_wt
arg_ba	1																		
arg_ma	0.57	1																	
arg_ri	-0.13	-0.3	1																
arg_wt	**0.68***	**0.85***	-0.29	1															
bra_ma	0.08	-0.52	0	-0.17	1														
bra_ri	-0.52	0.11	-0.3	-0.09	-0.58	1													
bra_wt	0.37	0.22	0	0.13	-0.16	-0.53	1												
chl_cg	-0.03	-0.58	0.27	-0.54	0.56	-0.62	0.04	1											
chl_wt	0.53	0.33	-0.25	0.19	-0.12	0.12	-0.18	0.03	1										
col_ri	-0.03	0.49	0.22	0.44	-0.52	0.28	0.07	**-0.72***	-0.45	1									
per_cg	-0.04	-0.28	-0.28	-0.31	0.29	0.18	-0.09	-0.13	0.05	-0.07	1								
per_ri	0.17	0.21	-0.1	-0.03	-0.12	0.37	-0.42	-0.18	0.53	0.08	0.58	1							
pry_cg	-0.28	0.39	0.11	0.06	-0.48	0.19	0.04	-0.04	-0.03	0.16	-0.64	-0.15	1						
sac_cg	-0.27	-0.61	-0.03	-0.56	-0.03	0.38	-0.25	0.06	0.19	-0.32	0.48	0.19	-0.59	1					
sac_ri	0.05	0.36	-0.35	-0.03	-0.63	0.43	-0.02	-0.11	0.36	0.1	0.11	0.54	0.21	0.15	1				
sac_wt	-0.13	-0.25	-0.06	-0.59	-0.33	0.09	0.4	0.29	0.3	-0.45	0.17	0.07	0.07	0.5	0.46	1			
ury_cg	-0.55	-0.24	-0.25	-0.07	0.33	0.06	-0.23	0.12	-0.48	-0.16	-0.33	-0.59	0.32	-0.29	-0.41	-0.35	1		
ury_ri	-0.14	0.38	-0.17	0.2	**-0.87***	**0.68***	-0.08	-0.6	0.01	0.56	-0.13	0.15	0.16	0.24	0.66	0.13	-0.24	1	
ury_wt	-0.07	-0.35	**0.82***	-0.09	0.39	-0.45	-0.25	0.4	-0.28	0.04	-0.42	-0.29	0.02	-0.19	-0.63	-0.46	0.14	-0.42	1

scenario H 2001-2010	arg_ba	arg_ma	arg_ri	arg_wt	bra_ma	bra_ri	bra_wt	chl_cg	chl_wt	col_ri	per_cg	per_ri	pry_cg	sac_cg	sac_ri	sac_wt	ury_cg	ury_ri	ury_wt
arg_ba	1																		
arg_ma	0.11	1																	
arg_ri	0.26	-0.03	1																
arg_wt	0.35	0.25	0.59	1															
bra_ma	-0.38	-0.19	-0.06	0	1														
bra_ri	-0.09	0.2	**-0.73***	-0.45	0.2	1													
bra_wt	-0.28	-0.37	0.41	0.07	**0.74***	-0.32	1												
chl_cg	0.45	0.23	0.46	0.61	-0.41	**-0.75***	-0.14	1											
chl_wt	-0.21	0.42	0.22	0.01	-0.29	-0.21	-0.22	0.07	1										
col_ri	-0.15	0.24	-0.09	-0.1	0.07	-0.33	0.2	0.4	0.17	1									
per_cg	-0.58	-0.18	-0.24	-0.59	0.45	0.17	0.29	-0.5	0.36	0.37	1								
per_ri	-0.37	-0.31	-0.12	-0.3	0.23	-0.3	0.26	-0.04	0.41	0.31	0.54	1							
pry_cg	0.25	-0.11	-0.29	0.18	0.63	0.41	0.24	-0.2	-0.51	0.03	0.07	-0.15	1						
sac_cg	**0.76***	-0.23	0.38	0.38	0.11	-0.31	0.16	0.43	-0.28	0.04	-0.18	-0.06	0.51	1					
sac_ri	-0.16	0.13	-0.27	-0.1	0.51	0.25	0.04	-0.21	0.36	0.22	0.66*	0.51	0.46	0.2	1				
sac_wt	0.42	0.25	**0.87***	0.6	0.04	-0.42	0.37	0.31	0.16	-0.22	-0.39	-0.24	-0.11	0.36	-0.21	1			
ury_cg	0.59	0.28	**0.66***	0.29	-0.29	-0.35	0.08	0.46	-0.07	0.07	-0.37	-0.56	-0.18	0.44	-0.42	0.69*	1		
ury_ri	0.43	-0.24	-0.12	-0.23	-0.05	0.46	-0.12	-0.53	-0.03	-0.59	-0.05	-0.02	0.25	0.22	0.08	0.12	-0.08	1	
ury_wt	0.5	0.14	0.54	0.16	-0.29	-0.09	-0.09	0.16	-0.06	-0.21	-0.2	-0.68*	-0.11	0.39	-0.3	0.52	0.86*	0.1	1

Oceania

scenario L 1992-2000				
	aus_ba	aus_ri	aus_wt	nzl_cg
aus_ba	1			
aus_ri	-0.45	1		
aus_wt	**0.97***	-0.42	1	
nzl_cg	-0.2	0.27	-0.08	1

scenario H 2001-2010				
	aus_ba	aus_ri	aus_wt	nzl_cg
aus_ba	1			
aus_ri	0.07	1		
aus_wt	**0.98***	0.08	1	
nzl_cg	-0.33	0.17	-0.27	1

North Africa and the Middle East

scenario L 1992-2000							
	dza_cg	dza_wt	egy_cg	egy_ri	egy_wt	mle_cg	mle_wt
dza_cg	1						
dza_wt	**0.95***	1					
egy_cg	0.22	0.12	1				
egy_ri	0.13	0.11	**-0.71***	1			
egy_wt	0.42	0.5	0.36	**-0.67***	1		
mle_cg	0.41	0.38	-0.3	0.49	-0.2	1	
mle_wt	0.31	0.42	-0.53	0.54	-0.06	**0.72***	1

scenario H 2001-2010							
	dza_cg	dza_wt	egy_cg	egy_ri	egy_wt	mle_cg	mle_wt
dza_cg	1						
dza_wt	0.29	1					
egy_cg	0.47	0.19	1				
egy_ri	0.39	0.54	0.04	1			
egy_wt	0.38	0.06	-0.09	0.45	1		
mle_cg	-0.41	0.5	-0.24	-0.1	-0.62	1	
mle_wt	-0.44	0.49	-0.26	-0.14	-0.34	**0.91***	1

Subsaharan Africa

scenario L 1992-2000										
	gha_cg	gha_ri	moz_ri	nga_ri	sdn_cg	sdn_wt	tza_cg	tza_ri	zaf_cg	zaf_wt
gha_cg	1									
gha_ri	0.29	1								
moz_ri	0.51	0.02	1							
nga_ri	-0.02	0.01	-0.5	1						
sdn_cg	-0.18	-0.66	-0.21	0.18	1					
sdn_wt	-0.4	0.37	0.32	-0.35	-0.41	1				
tza_cg	0.52	0.13	0.49	0.21	0.07	-0.14	1			
tza_ri	**0.68***	0.51	0.3	-0.12	-0.04	-0.21	0.46	1		
zaf_cg	0.55	0.24	0.66	-0.49	-0.13	0.24	-0.01	0.54	1	
zaf_wt	-0.34	-0.31	-0.04	-0.06	0.5	0.04	-0.16	0.15	0.19	1

scenario H 2001-2010										
	gha_cg	gha_ri	moz_ri	nga_ri	sdn_cg	sdn_wt	tza_cg	tza_ri	zaf_cg	zaf_wt
gha_cg	1									
gha_ri	**0.63***	1								
moz_ri	0.15	0.1	1							
nga_ri	0.53	0.17	-0.53	1						
sdn_cg	-0.28	-0.2	0.16	-0.56	1					
sdn_wt	-0.17	0.14	0.37	**-0.71***	0.55	1				
tza_cg	-0.25	-0.01	-0.26	-0.25	-0.15	0.24	1			
tza_ri	0.06	0.08	0.22	-0.5	-0.06	0.39	**0.64***	1		
zaf_cg	**0.69***	**0.72***	0.05	0.48	-0.14	0.09	-0.19	-0.34	1	
zaf_wt	-0.25	0.02	-0.12	-0.17	-0.44	-0.03	**0.84***	0.59	-0.26	1

A5. Global correlation coefficients between RUK and Europe and between North America and Oceania calculated over 1992-2001 and 2001-2010

RUK (the Russian Federation, Ukraine, Kazakhstan) and Europe

scenario L 1992-2000	e15_ba	e15_ma	e15_wts	e12_ba	e12_ma	e12_wts	kaz_cg	kaz_wt	rus_ba	rus_wt	ukr_cg	ukr_wt
e15_ba	1											
e15_ma	**0.75***	1										
e15_wts	**0.88***	0.6	1									
e12_ba	-0.08	0.12	0.03	1								
e12_ma	-0.09	0.16	0.01	**0.90***	1							
e12_wts	-0.54	-0.14	-0.29	**0.67***	0.56	1						
kaz_cg	0.09	0.37	-0.17	-0.13	0.18	-0.34	1					
kaz_wt	-0.1	0.39	-0.34	-0.08	0.22	-0.11	**0.88***	1				
rus_ba	0.06	0.13	-0.29	-0.31	-0.21	-0.41	**0.71***	0.53	1			
rus_wt	-0.03	0.3	-0.45	-0.13	0	-0.27	**0.81***	**0.82***	**0.82***	1		
ukr_cg	-0.28	0.02	-0.57	0.24	0.2	0.28	0.29	0.36	0.48	0.64	1	
ukr_wt	-0.08	-0.1	-0.02	0.6	0.45	0.39	-0.28	-0.33	-0.41	-0.23	0.38	1

scenario H 2001-2010	e15_ba	e15_ma	e15_wts	e12_ba	e12_ma	e12_wts	kaz_cg	kaz_wt	rus_ba	rus_wt	ukr_cg	ukr_wt
e15_ba	1											
e15_ma	0.47	1										
e15_wts	**0.66***	0.5	1									
e12_ba	**0.66***	**0.64***	**0.79***	1								
e12_ma	0.11	0.08	**0.73***	0.45	1							
e12_wts	0.5	0.62	**0.83***	**0.89***	**0.72***	1						
kaz_cg	0.06	0.11	-0.3	-0.23	**-0.69***	-0.48	1					
kaz_wt	-0.05	0.28	-0.15	-0.01	-0.45	-0.19	**0.84***	1				
rus_ba	0.28	0.15	0.37	0.21	0.23	0.28	0.36	0.34	1			
rus_wt	0.41	**0.69***	0.47	0.43	0.12	0.48	0.41	0.49	**0.79***	1		
ukr_cg	0.53	0.4	**0.93***	**0.70***	**0.81***	**0.82***	-0.26	-0.11	0.56	0.56	1	
ukr_wt	0.39	**0.84***	**0.74***	**0.72***	0.54	**0.84***	-0.16	0.12	0.27	**0.63***	**0.73***	1

Oceania and North America

scenario L 1992-2000	can_wt	can_ba	can_ma	usa_wt	usa_ma	aus_wt	aus_ba
can_wt	1						
can_ba	0.66	1					
can_ma	0	0.2	1				
usa_wt	-0.01	-0.24	-0.06	1			
usa_ma	-0.11	-0.45	-0.1	0.26	1		
aus_wt	0.49	0.54	-0.21	0.08	-0.56	1	
aus_ba	0.38	0.47	-0.33	0.08	-0.63	**0.97***	1

scenario H 2001-2010	can_wt	can_ba	can_ma	usa_wt	usa_ma	aus_wt	aus_ba
can_wt	1						
can_ba	**0.95***	1					
can_ma	**0.83***	**0.68***	1				
usa_wt	0.59	**0.72***	0.44	1			
usa_ma	0.51	**0.68***	0.12	0.48	1		
aus_wt	0.25	0.46	0.08	**0.83***	0.31	1	
aus_ba	0.17	0.36	0.05	**0.82***	0.25	**0.98***	1