Analyzing Total Factor Productivity Effects of Agricultural Policies and Climate Change Using Production Function Models

Gerald D. Toland, Jr. and Raphael O. Onyeaghala
Southwest Minnesota State University, Marshall, Minnesota

Abstract

Our global agricultural economy is challenged with serving the nutritional needs of nine billion people by the year 2050. An estimated seventy-percent increase in agricultural production capacity is needed over the next thirty-five years to balance the growth trends of worldwide food supply and demand.

To investigate fundamental aspects of this challenge, we utilize a USDA-ERS production model (2003)[i] and an OECD model of sustainable growth to examine the economic factors required for sustainable Total Factor Productivity (TFP) growth.[ii]

We also review the effects of alternative institutional approaches, research funding policies, new technologies and climate change effects as critical determinants of global TFP growth rates required to meet growing worldwide food demands.

Introduction

In April 2014, former US Secretary of Agriculture Tom Vilsack articulated the record of growth in US farm output since the mid-20th Century:[iii]

> *"…Since 1950, our corn production increased 300 percent. …What this means is we've gone from planting 10,000 seeds per acre of corn to 30,000 seeds per acre…Also, the average dairy cow was producing 5,500 pounds of milk. Today, that same cow - 22,000 pounds of milk. … Extraordinary productivity [is] just based on the science.*
>
> *…World food needs …. grow as populations grow. … the challenge for agriculture [is] to meet the needs of 9 billion people…in the next 40 years … we have to increase agricultural production by about 70 percent.*
>
> *… [to meet this growing demand] we need to be investing significantly more resources in agricultural research than we've been in the past."*

Former Secretary Vilsack also addressed the related topic of how a changing climate influences the sustainability of future agricultural output:

> *"We ignore climate change at our peril… farmers, because they deal with their land every day, they understand the personality of their farm. …And so farmers are very interested in the…technologies that will allow them to…be productive even if they have less water, even if they have a storm that comes through that's extraordinarily intense. So they're very interested in investing in innovation…new seed technology and intellectual property and new machinery and new farming systems that will allow them to mitigate the impact of climate."*

Organization of this Research Paper

Because we are all ultimately food consumers, we share a universal interest in determining how our agricultural production capacity will sustainably keep pace with the growth in global food demand.

This topic's worldwide significance requires that we review the primary economic forces that guide sustainable agricultural production. We highlight the importance of basic and applied research, as well as other key influences, that regulate the growth of US and global agricultural productivity.

To guide our analysis, we initially utilize established production function theory and the latest empirical research. We aim to ascertain the factors most closely associated with past, present and future agricultural productivity trends.

Next we explore interrelationships among productivity, sustainability and climate change. These interactions shape agri-food system's capacity to respond to changing economic and environmental conditions.

Finally we seek additional insights about long-run sustainable agricultural production by examining the economic consequences of alternative policy options and outcomes.

Economic Forces Driving Change in Agricultural Productivity and Sustainability

Definitions and Terminology. Reliable scientific research depends on utilizing clearly-defined terms and commonly-recognized definitions. We begin by reviewing the nature and purposes of the widely-accepted total factor productivity (TFP) measures used throughout this paper.

Weighted-value Indices of Agricultural Outputs and Inputs. To properly estimate changes in overall agricultural productivity over time requires that we use reasonable and accepted methods of aggregating output and input values.

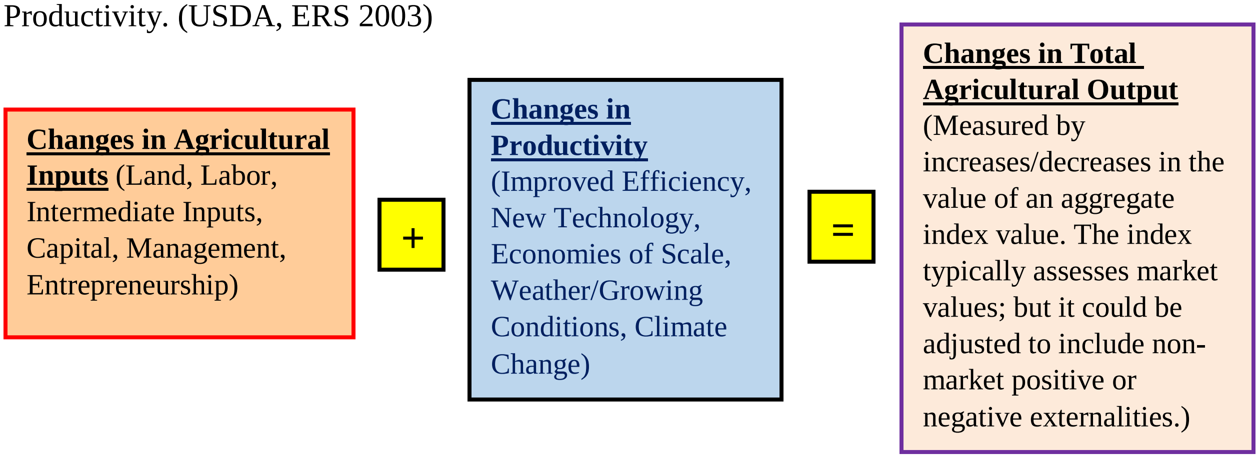
We adopt the index-estimation technique used by the US Department of Agriculture's Economic Research Service (USDA-ERS). The USDA-ERS provides website access to any researcher who seeks to utilize the data and estimation methods necessary for conducting empirical economic research on agricultural productivity trends. The USDA-ERS agricultural productivity indicator used in this paper is a weighted-average aggregate index value of each observation measured over time in relation to a base-period index value.

For example, if we are interested in the annual percent rates-of-change for agricultural output and/or agricultural inputs, then we determine growth rates in relation to base-year index values.

There are variety of techniques available to calculate indices for time-series data. Following USDA-ERS procedures, the data and trends reported in this paper rely upon the Tornqvist Index-Estimation Methodology.[iv]

Differentiating Changes in Agricultural Output and Changes in Agricultural Productivity. US Agricultural Output, when measured as an aggregated index value, is an estimate of total US agricultural production in a particular time period. In Figure 1.1 below, we use a USDA-ERS production model (2003) to illustrate that US agricultural output levels are a function of both input-usage-rates and productivity-changes.[v]

Figure 1.1 – Agricultural Output Changes Are Determined by Changes in Inputs and Productivity. (USDA, ERS 2003)



The equation in Figure 1.1 allows us to visualize multiple sources of net change in Total Agricultural Output (the equation's rightmost box). The leftmost box emphasizes economic conditions where producers hire additional inputs to increase Total Agricultural Output. The middle flowchart box highlights productivity factors such as improved technologies, variable weather patterns, or permanent changes in climate associated with variations in total agricultural output.

The content of the rightmost box in Figure 1.1 also suggests that the standard reports of market-based-indices of total agricultural output can be modified to include the effects of non-market externalities into the calculation.

For example, agriculture produces the positive externality of carbon sequestration, and is also a source of non-point water pollution (negative external effect). At this time, most indexed agricultural output measures are "traditional" – they simply calculate readily-available and widely- recognized changes in market-based indexes of total output. Adjusting indexed-output-values for external effects is a technique receiving increased attention, but more work is needed to create a universally accepted measure of external impacts.[vi]

The USDA-ERS regularly collects data to develop reliable indices of traditional market-based agricultural input and output values. To measure *"Changes in Productivity"* (middle box, Figure 1.1), the USDA-ERS closely monitors the Ratio of Total Agricultural Output to Total Agricultural Inputs. This ratio is known as ***Total Factor Productivity (TFP)***. Whenever the TFP ratio increases over time, it indicates that average agricultural output per unit input is rising. Simply put, we declare that overall productivity is growing when the TFP trend is increasing.

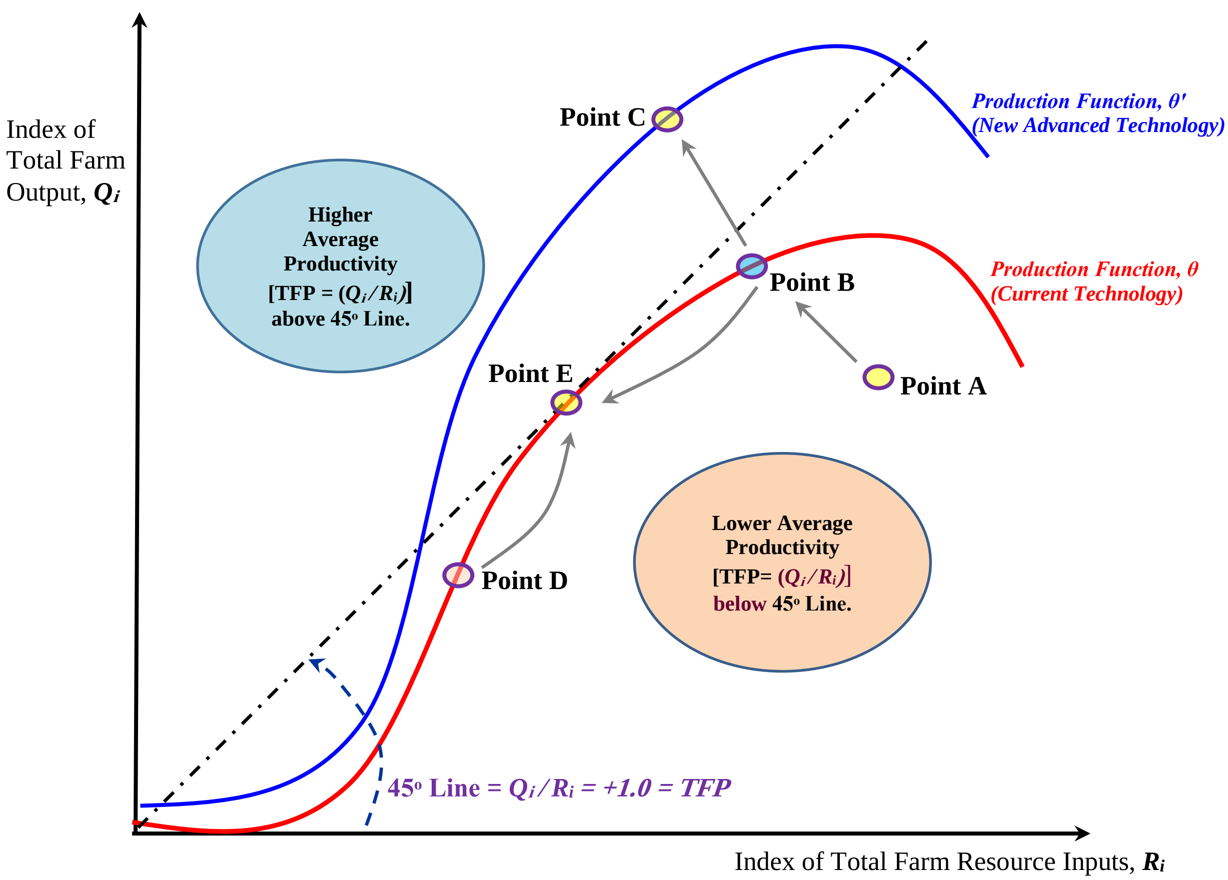
TFP growth can be a powerful economic force. Other things being equal, increased TFP means that a farm owner-operator can increase competitiveness, reduce average production cost and improve profit margin. From a societal standpoint, improved TFP can alleviate the general economic challenge associated with allocating scarce resources.

TFP Growth and the Technological Treadmill. There is an economic downside to TFP growth. As increased TFP enhances the individual financial condition of each farm enterprise, the ***fallacy of composition***[vii] takes hold. The fallacy means that a rising-TFP has market-wide consequences that differ greatly from the individual producer's cost-saving TFP benefits.

When applied to agriculture, the fallacy is sometimes better known as *the* ***"technological treadmill"*** (Cochrane, 1958; Levins and Cochrane, 1996).[viii],[ix] The treadmill analogy is appropriate. Farm producers know their fast pace of technology adoption is necessary just to keep-up with competitive market demands.

Analyzing TFP Changes Using Production Function Analysis. The Organization for Economic Cooperation and Development (OECD), in a research report on sustainable agricultural productivity growth, used production function analysis to highlight sources of TFP growth.[x] The OECD study identifies technical efficiency gains, technological advance, and economies of scale as primary pathways to realize TFP growth. See Figure 1.2 below.

Figure 1.2 – Production Function Analysis of the Alternative Paths to Achieving Increased Total Factor Productivity (TFP) ***(OECD 2011)***[xi]



<u>Legend for the Production Functions, $Q_i = \theta(R_i)$ and $Q_i = \theta'(R_i)$, in Figure 1.2:</u>

- Output (Q_i) Changes from **Point A** to **B**: ***Improved TFP from Gains in Technical Efficiency***
- Output (Q_i) Changes from **Point B** to **C**: ***Technological Advance Increases TFP***
- Output (Q_i) Changes from **Point B** to **E**
  or Output (Q_i) Changes from **Point D** to **E**: ***Improved TFP from Economies of Scale***

Analyzing TFP Changes Using Production Function Analysis. We use the graph in Figure 1.2 to emphasize that TFP growth originates from multiple sources. This analytical approach also suggests that we can encourage additional gains in TFP by carefully designing policies to promote gains in technical efficiency, technological advance and economies of scale. It is instructive to review the reasons for gains in total agricultural factor productivity.

<u>Technical Efficiency</u> (Point A to B in Figure 1.2). Technical Efficiency produces gains in output capacity when farm operators change short-run resource allocations and improve management decisions to realize the full productive potential of current technologies.

<u>Technological Advance</u> (Point B to C in Figure 1.2). Technological Advance generates production gains by introducing new technologies that reorganize resource use to create increased output per unit of total input.

<u>Economies of Scale</u> (Point D to E, or Point B to E, in Figure 1.2). Economies of Scale advances total output because a farm production unit achieves heightened long-run output efficiencies. A farm operation benefits by proportionately changing its input levels to achieve maximum average productivity and minimum average total cost per unit of output.

Empirical Research on Changes in US Agricultural TFP. In July 2015, the USDA-ERS released an extensive study of US agriculture that examined the trends and sources of changing US farm productivity.[xii] When we compare the theoretical concepts in Figure 1.2 to the USDA-ERS empirical research on agricultural output and productivity, we observe logical connections.

In particular, the USDA-ERS review of US agricultural productivity identifies "drivers" that have influenced past and current TFP trends, as well as factors that will continue to strongly influence future TFP growth.

The in-depth USDA-ERS productivity study made the following key observations and interpretations:[xiii]

- The USDA-ERS Study reviewed 63 years of US agricultural productivity data between 1948 and 2011. When the weighted-average index of all farm inputs (land, labor, intermediated goods, and capital) was estimated over this time span, the results were notable for how efficient those resources were utilized. <u>Aggregate input use</u> increased at a modest rate of 0.07% per year.

- During the 1948-2011 timespan, the aggregate <u>agricultural output index</u> increased at a 1.49% annual rate.

- When we combine the results of input use and output generation, we determine that TFP grew at an average rate of 1.42% per year. This is an impressive result. Over the entire 1948-2011 observation period, <u>aggregate output</u> increased by 156%, and the major share of that growth is attributable to the gains in TFP.

If we interpret the reported USDA-ERS productivity patterns using our production functions displayed in Figure 1.2, we can reasonably state that the growth in US agricultural output is primarily attributable to both *technical efficiency gains* and *technological advance*. In Figure 1.2, we can demonstrate these output increases as movements between Points A and B, and between Points B and C.

We make this interpretation because efficiency gains and technological progress require very little or no change in the use of agricultural inputs; and the 1948-2011 record shows that the output growth rate (1.49% per year) is approximately 21.3 times larger than aggregate input growth rate (0.07% per year).

From years of well-established empirical research, we also know that US agriculture has seen both the *average farm acreage size increase* and the *number of farms decrease*. It is also true the total amount of US land in agricultural production gradually decreased during 1948-2011.[xiv]

As US farm producers managed their operations to achieve tremendous gains in output growth between 1948 and 2011, they did not demand more land area to accomplish that feat. The extensive agricultural land input, measured in acres, lessened.

When we measure US agricultural productivity gains, some changes in TFP are traceable to economies of scale. But variations in scale-of-operation are also associated with the drive for improved efficiency and technological advance. As a result, the aggregate output trends that are directly linked to economies of scale are difficult to separate-out from the overwhelming incentives for producers to adapt their operations to new efficient methods and technologies.

Empirical Research on Global Agricultural TFP Growth, and TFP Trends in the EU. Total world agricultural output also increased above the levels achieved in the 1990s. During 2001 – 2014, global agricultural output expanded at an average rate of 2.54 percent per year. This expansion is primarily attributed to improvements in TFP across the globe. TFP accounted for 1.71 percent of the 2.54 percent (about two-thirds) of global agricultural output growth.[xv]

Developing countries have continued to experience a TFP growth rate above the global average. These nations can take advantage of gains in technical efficiency, technological change and improved productivity via economies of scale. In contrast, agricultural TFP growth in developed nations has been slower. In Europe, during the 2001 – 2014 period, the TFP growth rate in Europe was 1.67 percent, just slightly below the world 1.71 percent TFP growth rate.[xvi]

Latin American and North American growth rates were 1.98 percent and 1.89 percent, respectively. Other parts of the world show a positive correlation between TFP and gains in total agricultural output.[xvii]

A recent European Commission (EC) report in December 2016 cites research demonstrating that TFP gains are associated with revised Common Agricultural Policy (CAP) policies that decouple program incentives from market incentives. These policy studies suggest that CAP reform can create positive effects on TFP growth. [xviii]

The process of reviewing and reforming regional agricultural policies is a worthwhile endeavor, especially when the global agricultural economy is searching for ways to improve the nutrition and diets of a growing world population.

Recent US TFP Trends and Research Opportunities. In May 2016, the USDA-ERS posted an online updated report of US Agricultural TFP entitled, "*Findings, Documentation and Methods.*"[xix] The published results largely confirmed the outcomes identified in the earlier 1948-2011 ERS productivity study.

The 2016 ERS online-post took advantage of additional farm TFP data compiled during the 2012-2013 period. Consequently, we can reliably examine US agricultural TFP trends during 1948-2013. The supplementary TFP data enabled the ERS to determine whether current TFP growth is keeping pace with historical trends.

Trends in TFP growth are now a key focus for policy-makers everywhere because the capacity to sustainably meet an expanding global food demand is a genuine concern. The problem of how we balance worldwide food production with an enlarging global food demand as our planet's climate changes is not easily solved. As a result, studies of regional and global agricultural TFP growth are increasingly important.

The 2016 USDA-ERS report compares changes in US agricultural productivity in two recent and separate sub-periods: **2000-2007** and **2007-2013**. ERS defines a sub-period as the time required for the completion of a peak-to-peak cycle of aggregate economic activity.

The **2000-2007** sub-period was characterized by a surge in US bio-fuel use and production. Over the early 2000's timespan, US corn acreage expanded by nearly 15 million acres, corn prices rose, and the US rural economy experienced growth in capital investment and job creation. Agricultural input demand was noticeably higher during this cycle of booming bio-fuel markets. The ***ag-input utilization index*** rose by +0.32% per year in the 2000-2007 sub-period, compared to the long-term historical average of +0.07% per year.[xx]

The rate of US total ***agricultural output growth*** slowed somewhat, increasing an average of +0.9% per year, during both the 2000-2007 and the 2007-2013 sub-periods.

When we determine the combined effect of a slower +0.9% output growth rate and an accelerated 0.32% input hiring rate, we notice that US agricultural **2000-2007** TFP growth <u>decelerated</u> to a +0.58% rate per annum (compared to the US 1.42% TFP growth rate that prevailed during 1948-2011).[xxi]

Slackening of the US TFP growth rate in **2000-2007** sub-period might have been a cause for concern. But the **2007-2013** sub-period created a completely different dynamic. During **2007-2013**, the US experienced the convergence of three important phenomena: (1) the 2008-2009 US national macroeconomic recession, (2), the increased use of precision technologies in US agriculture, and (3) a spurt in export demand growth for US agricultural and food products.

From the standpoint of TFP growth, the **2007-2013** economic cycle differentiated itself because of a remarkable <u>−0.54% per year</u> decrease in the US agricultural input-use rate. When we combine the negative change in the input index with the +0.9% output growth, the <u>change in TFP rose to a +1.54% annual growth rate</u> during the 2007-2013 sub-period, as compared to the +0.58% annual rate during the 2000-2007 sub-period. This upward jump in the US agricultural TFP growth rate is large enough to merit a serious discussion of its origins.[xxii]

The US national recession during 2008-2009 was the most severe since the 1930's Great Depression, and some of the reduced agricultural input usage during the 2007-2013 sub-period can be attributed to this massive macroeconomic downturn. However, another researchable hypothesis is the influence of precision agricultural technology on farm input usage rates during the **2007- 2013** sub-period.[xxiii]

While precision agriculture methods require up-front software and hardware investments, the payoff for producers is the ability to apply extra inputs only in areas that are identified as deficient or would benefit from additional application. The savings in resource usage-rates associated with precision agricultural practices can be measured in terms of reduced pesticide and fertilizer use, decreased labor time, and related general efficiencies. These reductions in overall input use are significant.

In addition, there are opportunities to achieve increased efficiencies in the use of natural resources such as land and water. Producers can: (1) adopt smarter technologies to improve water irrigation efficiency, (2) invest in anaerobic digesters to generate energy and reduce emissions from farm "waste material", and (3) incorporate farming practices that reduce soil erosion rates.[xxiv]

Integrating Sustainability and Climate Change Considerations with Productivity Analysis

Traditional market-based productivity indices show a continuing upward TFP trend. While US agricultural TFP data reflect an impressive record of farm output expansion, researchable questions remain about future sustainable growth. A variety of intensive agricultural practices are associated with damaging environmental side effects.

Concerns about sustainability are also intertwined with climate-change conditions. At this time there are more questions than there are answers. A growing research agenda is focused on how environmental degradation and a changing climate influence the future growth of agricultural productivity.

Linking Sustainability to Agricultural Productivity. In the journal *Nature* (2002), Tilman, et al. agreed that global agricultural technologies have significantly boosted the worldwide food supply.[xxv] However, this research group also notes the unintended but harmful effects of many global farm systems on environmental quality and ecosystem carrying-capacity. Krutilla [xxvi] and other researchers have arrived at similar conclusions.

Today, a growing number of producers are adapting new techniques that increase farm output while preserving future ecosystem services.[xxvii] The expanded focus on *"sustainability"* implies that agriculture should develop and implement environmentally-friendly production methods that also meet current global food needs. If we can implement sustainable farming systems now, then future generations can also share the same benefits that we enjoy today: utilizing natural resources and environmental systems to support a successful economy and a desirable quality of life.

Organizations such as the OECD (2014) and the United Nations [UN] (2013) sponsor ongoing research to encourage globally-sustainable agricultural growth trends.[xxviii],[xxix] For example, the OECD's *Green Growth* initiative aims to spur modernization and technological improvements to promote growth patterns that can simultaneously maintain current prosperity while also conserving natural resources and environmental conditions necessary for future health and welfare.[xxx]

Similarly, the UN *Sustainable Development Solutions Network* champions actions such as food-waste reduction, healthy-diet programs, sustainable production technology adoption, and the creation of climate-smart agricultural landscapes.[xxxi] Conservation programs sponsored by the USDA also play a role in identifying specific programs, such as soil health workshops and cost-shared practices that promote sustainable production.[xxxii]

Climate Change and Agricultural Productivity: Challenges and Opportunities. If we were living in climate-stable world, questions about sustainable agricultural production growth would still merit attention. But overwhelming scientific evidence is telling us that the global climate is shifting, and consequently we have heightened interest in sustainability. In March 2014, the Intergovernmental Panel on Climate Change (IPCC) used the results of extensive and credible research to declare that climate transformation is already in progress, and further variation is expected.[xxxiii]

While researchers have worked diligently to construct sophisticated models to simulate and predict interactions between agricultural output trends and climate change, the complexity of the challenge is daunting.

From a biophysical standpoint, it is not just a matter of increased average global temperatures and melting ice caps. The higher concentrations of carbon dioxide (CO_2) and Ozone (O_3) in the earth's atmosphere influence plant transpiration and growth rates. A more energized atmosphere also increases the potential for extreme weather events such as extended droughts or flash floods.[xxxiv]

From an economic standpoint, forecasting changes in agricultural productivity go beyond the pure biochemistry and physics of new ecological conditions. Output trends are intertwined with the collective influence of a shifting global climate on the behavioral incentives facing individual farm producers and consumers. Predicted output trends should also reflect how macro- and micro-economic market conditions, as well as government policies, respond to the new circumstances.

Lobell and Gourdji (2012) carefully examined the biophysical effects of projected climate conditions on global crop productivity.[xxxv] Lobell and Gourdji determined that increased CO_2 concentrations would tend to increase crop yields globally, while warming trends would likely offset most of the CO_2 impact by reducing average worldwide yields.

In addition, this biophysical research assesses that climate change will <u>slow the rate of expected productivity growth</u> normally connected with new technologies and improved management methods. Lobell and Gourdji (2012) conclude that climate change will not reduce global yields, but will make it more difficult for agricultural productivity to expand as rapidly as would be expected in an alternative climate-stable scenario.

Nelson, et al. (2013) undertook the large task of combining biophysical and economic models, and analyzed multiple scenarios to increase our understanding of the range of possible future outcomes.[xxxvi] The complexity of their research assignment is made clear when we understand that Nelson, et al. utilized the outcomes of seven different biophysical scenarios as inputs into nine separate economic models. Simple arithmetic tells us that tracking the effects of climate change requires us to anticipate the outcomes of at least 7 x 9 = 63 possible scenarios.

When they consolidated the results from this multi-faceted approach, Nelson et al. (2013) determined that by 2050, climate change will be associated with a 17% loss in global yields, but the lost productivity will be nearly offset by an escalating intensity of farm practices and increased farmed-acreages, creating a net 2% output loss. Their much more dramatic predictions were economic.

The Nelson, et al. model estimated that global consumption will drop by 3% and average producer prices will rise by about 20%. While Nelson et al. (2013) were not charged with the goal of forecasting the negative welfare impacts of rising global food prices on low-income households, the predicted results of their extensive modeling effort are a reason for considerable concern.

Similar to Nelson, et al., Yang and Shumway (2015) utilized sophisticated modeling techniques to predict how climate change would produce structural economic changes in US agriculture.[xxxvii] The differentiating aspect of Yang and Shumway's research is their focus on the predicted adjustment rate for asset utilization as climate change alters market conditions. Yang and Shumway used over 100-years of data to demonstrate that new market situations (created by a stochastic climate or similar dynamic force) cause quasi-fixed asset modifications – meaning that the farm assets are not totally fixed, nor are they instantaneously reallocated.

Evidence is strong for quasi-fixity in Yang and Shumway's analysis. While no enterprise adapts immediately, crop adjustments are predicted to occur at two-times the rate compared to livestock changes. Yang and Shumway also employ the economic theory of rational expectations to demonstrate that farm production adjustment rates are much slower and the economic costs are much higher if producers fail to anticipate climate change.

On other hand, if producers accept that climate change is real, and simply adapt to climate uncertainty, then adjustment costs drop noticeably and the asset reallocation rate for quasi-fixed assets rises. We previously noted the US Agriculture Secretary's warning that we ignore climate change at our peril; his viewpoint is validated by Yang and Shumway's in-depth study of stochastic asset adjustment.

Alternative Agricultural Productivity Scenarios and Associated Policy Options

It is difficult to overstate the importance of ongoing research to determine both the obstacles and the catalysts for continued agricultural productivity growth. Factors such as environmental sustainability and climate change deserve attention if we are to better understand how current conditions influence future trends. The common threads that tie together the entire discussion are the need to both expand our knowledge base and harness the necessary incentives, if sufficient US and global agricultural productivity growth is to occur in the 21st-Century.

Fortunately, we do not have to create TFP-enhancing strategies "from scratch." There are fundamental principles that guide productivity growth, and we can use them to establish plausible scenarios and policy options. In the 2003 edition of *Agricultural Resources and Environmental Indicators,* the USDA's Economic Research Service (ERS) highlighted the following factors closely associated with productivity growth:[xxxviii]

- Research and Development (R&D)
- Extension
- Education
- Infrastructure
- Government policies/programs

Research and Development (R&D). Innovation in agriculture, as in most industries, is the primary source of TFP growth. Innovation can be small- or large-scale, but its origins are most often the result of systematic investigation, i.e., research and development (R&D). In agriculture, R&D is typically responsible for outcomes such as disease-resistant and higher-yielding crops, improved livestock breeds, enhanced fertilizer and pest-management systems, and superior farm practices.

Twenty-first Century R&D is both privately- and publicly-funded, and US private sources now generate a majority of agricultural research expenditures. While there are exceptions, we can distinguish private R&D from public R&D by examining their intended purposes. Private research is most often focused on specific and commercially-viable applications, while public funds are primarily channeled towards basic research.

Private firms typically strive to retain intellectual property rights for their innovations via legal mechanisms such as patents, copyrights and trademarks. The private focus on proprietary rights is essential if the originators of a new process or product are to reap a sufficient return on their R&D costs.

Despite the best legal efforts of private enterprise, newly-created knowledge from R&D often generates significant positive externalities. Private firms cannot always capture all of the research benefits that they create. Information about new methods frequently spreads quickly and at low cost to the rest of the economy. As a result, knowledge-creation unavoidably creates "public good" outcomes – non-rival and non-excludable benefits.

In comparison to commercially-oriented R&D, the benefits of basic research are even more clearly in the realm of public goods. Consequently the use of public funds to engage in basic research is economically sensible. Private firms could not earn sufficient returns, and the private market would under-allocate resources towards Basic R&D.

R&D often yields benefits that are not purely public or private. In such instances, a rationale for private-public partnerships arises. In fact, without an appropriate institutional apparatus, important and productive research opportunities requiring private-public collaboration would be lost or overlooked.

Recognition of this potential R&D shortcoming led the US Congress to pass the 1980

Technology Innovation Act, and later the 1986 Technology Transfer Act (TTA). The TTA authorized federal departments to establish private-public alliances for joint research.[xxxix] More specifically, the TTA created legal guidelines to arrange private-public contracts known today as Cooperative Research and Development Agreements (CRADA's). The USDA quickly recognized the CRADA as a worthwhile institutional innovation. During 1987-1995 alone, USDA collaborated with private entities to implement over 500 CRADA's.[xl]

Joint CRADA projects, along with purely-private and purely-public R&D, together create the primary sources of agricultural TFP growth. The key role of R&D is the social rate of return on these research-oriented activities. Estimates for core marginal rates of return, reflecting directly-measurable and properly-discounted benefits and costs, fall anywhere between a +35% and +60% internal rate of return,[xli] when all private and public investments in agricultural R&D are included. Such returns are a sizable net gain to society, and highlight the importance of continued support for R&D from all sources.

Extension and Education. What time interval is needed for research breakthroughs to affect real output? What factors connect R&D innovations to actual productivity changes? Extension and education efforts are key links in disseminating, communicating and implementing new ideas.

While each system has a separate purpose, extension and education effectively reduce the time required to convert potential research gains into realized returns. If we first focus on the role of agricultural extension agents, we discover a group of professionals dedicated to organizing scientific results into easy-to-use formats. Extension's timely delivery of accessible information means that farmers and ranchers can quickly convert new knowledge into practical technologies that increase their operational efficiency and productivity.

Unfortunately, data on the productivity-enhancing effects of extension activities is sparse relative to the evidence of output gains from research. Scant data is one reason why the measured return on investment for extension efforts is variable, ranging between a 20% and a 100% rate of return.

Extension's purposes are being modified by the 21st-Century phenomena of the Internet. Producer access to self-help technologies, and the rapidly rising influence of private agricultural consulting firms, has lessened the private producer demand for USDA extension services. Federal government funding support for extension has fallen since 1980. State and local governments have found it necessary to reduce the number of agents, and consolidate county-level extension programs into larger regional service areas. Private consulting and self-service technologies are partly filling the void created by diminished investments in extension.

Extension programs facilitate the dissemination of specific innovations and technologies to producers. Education, on the other hand, aims to build broad skills in critical thinking and problem solving. Fuglie, et al. (2007) estimated that 5.6% of US agricultural output growth could be attributed to increased labor quality.[xlii]

When the farm labor force is better educated, has superior training or gains more experience, then labor quality improves. Additional education facilitates producer technology adoption, as well as teaching consumers the skills they need to properly evaluate new food choices based their actual benefits and risks. Producers surveyed by Joreger, et al. (2003) indicated their involvement the Minnesota Farm Business Management Education program was associated with a $5,000 average annual increase in net farm income (Joerger, 2003, p. 56).[xliii]

Infrastructure and Government Policies/Programs. Economic research determined that public infrastructure investments (roads, bridges and highways, water and sewer systems, schools, hospitals, etc.) are linked to gains in productivity. In agriculture, improved transportation and communication systems increase producer efficiencies for input acquisition and output marketing. Munisamy and Roe (1995) determined that infrastructure development and R&D were complementary inputs to agricultural productivity gains.[xliv]

Short and long run agricultural productivity patterns are induced by government policies. Let's first look at temporary government influences. When US federal biofuel policies dramatically increased corn production incentives in the early 2000's, producers responded with the rapid hiring of additional inputs (e.g., planting extra corn acres on marginal land) and the TFP growth slowed. By 2012, the federal government reduced or eliminated the majority of biofuel subsidies and corn output expansion leveled off. Input usage dropped, and farmers were also quickly adapting precision agriculture farming techniques. TFP was on the rise again.

Long term government effects on productivity include macroeconomic policies that encourage technological investments. Government programs that boost agricultural research and innovations also affect long term TFP. Other broad policies with extended effects include improved mechanisms to protect intellectual property rights and programs similar to CRADA. Legal protections create the correct economic environment for private and public research, because firms will innovate more rapidly if they have confidence in their ability to reap sufficient returns on their investments. We should also recognize the role of international trade policies and agreements that spur US agricultural producers to expand output when they have a global comparative advantage.

Alternative Research Policies and Associated Agricultural Productivity Scenarios. The in-depth 2015 ERS agricultural productivity study referenced earlier in this chapter not only reviewed past farm output developments, but also offered short and long term US TFP projections up through the year 2050.[xlv] ERS developed three TFP scenarios to explore the output growth consequences of different future funding levels for public research.

We can summarize the three alternate ERS assumptions about public agricultural research funding:[xxxviii]

- (#1) The Optimistic Scenario: U.S. public agricultural research spending rises an average of 1% per year percent in real terms, compared to the baseline of the 2005-09 average level of expenditures.
- (#2) The Nominally-Constant Annual Public Funding Scenario: Annual U.S. public agricultural research spending through 2050 remains unchanged in nominal dollars at its average 2005-09 level of $2.5 billion per year.
- (#3) The Scenario of a One-time 25%-Decrease in Federal Public Research Spending: In

this scenario, no subsequent nominal or real funding changes occur if Congress were to significantly reduce public agricultural research in 2014, and then maintains this lower level of public funding indefinitely into the future.

The above three scenarios are distinct federal agricultural research policy choices. Initially, the outcomes of these three funding options do not differ by much. Positive agricultural output growth is projected in all three situations through the year 2020; specifically, US farm production increases by 13%, 12% and 12%, respectively, in each of the three scenarios during the 2010-2020 stretch of growing seasons. Noticeably different outcomes occur when the entire 2010-2050 projection period is analyzed.

If we review the *optimistic scenario*, the expected TFP growth rate is 1.46 percent/year during 2010-50, compared with 1.42 percent during 1948-2011. From the standpoint of the future global food supply-demand balance, this is a good outcome.

The *scenario of constant nominal annual public funding* is not as 'rosy' as the optimistic one. The annual rate of agricultural TFP growth is 0.86%/year between 2010 and 2050; this is 40% lower than the 1.42%/year historical 1948-2011 growth rate. The predicted result of this policy option is strongly and negatively affected by a 3.73% per year increase in expected real research costs projected over the 2010-2050 forecasting interval.

The third scenario, *where public agricultural research experiences a 25% loss of funding in 2014, and then remains nominally constant per year in future years*, US Agricultural TFP growth rate decreases to 0.63%/year during 2010-50. This is a 56% reduction in TFP growth, relative to the 1.42%/year that the US experienced during 1948-2011.[xlvi]

Why do we care about the alternative growth TFP growth rates in these three scenarios? Heisey et al. (2011) projected that if Scenarios Two or Three become reality, then U.S. agricultural production growth rates likely will not match global food demand growth rates.[xlvii] In contrast, Heisey et al. (2011) also forecasted that if US R&D spending on public agricultural research were to rise by 1 percent per year in real terms subsequent to 2010, then U.S. agricultural TFP will expand at a rate *equal to* the speed of growing domestic and global food demand.

To meet global food demand, Scenarios #2 and #3 necessitate that US producers accelerate the rates at which they hire additional land, labor, capital, fertilizer, pesticide and related scarce inputs. The cost of production, and associated food prices, will rise as the marginal cost of hiring additional inputs increases. Increased worldwide food prices create severe burdens on low-income households across the planet.

Without sufficient gains in TFP (Scenarios 2 and 3), more intensive and extensive farmland-use is expected. Increased land use intensity, and increased hiring of extensive marginal lands for crop production, will create environmental challenges. We can expect compromised water quality, increased soil erosion, and reduced wildlife habitat and/or wetlands. The long run economic and ecological costs of Scenarios Two and Three are significant.

Summary and Conclusions

US Agricultural Productivity growth trends since 1950 have been sizable. More recent estimates of increased global TFP growth rates are also promising. Can these gains in TFP continue? Based on established theoretical and empirical evidence, answers to this questions are a largely a matter of policy choices. These are decisions with global consequences.

Is the US (and the world) prepared to select a path of sufficient investment in agricultural R&D to generate the TFP growth required to sustainably match the expected future increases in global food demand? This is a difficult question. Research tells us that we have the capacity to respond positively. Whether we will choose to expand TFP growth rates to meet global food demands is a challenge that requires us to effectively balance a variety of political, ethical, and economic considerations.

If we do answer this productivity challenge in a positive way, there are guideposts to guide the needed investments. A coordinated strategy to spur TFP growth will efficiently allocate the funding levels needed to support research and development (R&D), extension, education, infrastructure, and coordinated government policies/programs.

Research on TFP growth also informs policy design. Short and long run productivity trends often diverge. It is necessary to formulate productivity policies that intentionally consider both more immediate and extended outcomes and trends.

Endnotes

---

[i] Heimlich, Ralph. *Agricultural Resources and Environmental Indicators. Chapter 5: Agricultural Productivity and Research.* USDA, ERS. Agricultural Handbook 722. February 2003. http://infohouse.p2ric.org/ref/37/36628_files/AREI5-1productivity.pdf

[ii] OECD (2011), *Fostering Productivity and Competitiveness in Agriculture*, OECD Publishing. Page 25. Retrieved from: http://dx.doi.org/10.1787/9789264166820-en,

[iii] Council on Foreign Relations (CFR), Roger C. Altman, Presider "Agricultural Technology and Productivity Continue to Make Gains and Ensure U.S. Food Security: A Conversation With Tom Vilsack." CFR Events: Renewing America Series. April 9, 2014. Retrieved from: http://www.cfr.org/agricultural-policy/agricultural-technology-productivity-continue-make-gains-ensure-us-food- security/p35599

[iv] The Tornqvist index calculation technique incorporates prices from both the base period and the comparison period to determine the indexed weighted averages. A benefit of the Tornqvist method is that inputs to the production process need not be perfect substitutes.
Heimlich, Ralph. *Agricultural Resources and Environmental Indicators.* USDA, ERS Agriculture Handbook AH-722, Chapter 5.1, February 2003. Retrieved from: http://infohouse.p2ric.org/ref/37/36628.htm

[v] Heimlich, Ralph. *Agricultural Resources and Environmental Indicators. Chapter 5: Agricultural Productivity and Research.* USDA, ERS. Agricultural Handbook 722. February 2003. http://infohouse.p2ric.org/ref/37/36628_files/AREI5-1productivity.pdf

[vi] OECD (2014), Green Growth Indicators 2014, OECD Green Growth Studies, OECD Publishing. Retrieved from: http://dx.doi.org/10.1787/9789264202030-en

[vii] *Fallacy of Composition:* What is true for the individual is not necessarily true for the group. Samuelson, Paul and William Nordhaus. *Economics, Sixteenth Edition.* Boston: Irwin McGraw-Hill, 1998, pp. 6-7.

[viii] Cochrane, Willard W. 1958. Farm Prices. Myth and Reality. Minneapolis: University of Minnesota Press. Retrieved from: http://barrett.dyson.cornell.edu/Papers/IFPRIMay2002.pdf

[ix] Levins, Richard A. and Willard W. Cochrane. *"The Treadmill Revisited."* Land Economics. Vol. 72, No. 4 (Nov., 1996), pp. 550-553. Retrieved from: https://www.jstor.org/stable/3146915?seq=1#page_scan_tab_contents

[x] OECD (2011), *Fostering Productivity and Competitiveness in Agriculture*, OECD Publishing. Retrieved from: http://dx.doi.org/10.1787/9789264166820-en, page 25.

[xi] Wang, Sun Ling, Paul Heisey, David Schimmelpfennig, and Eldon Ball. *Agricultural Productivity Growth in the United States: Measurement, Trends, and Drivers*, ERR-189, U.S. Department of Agriculture, Economic Research Service, July 2015. Retrieved from: http://www.ers.usda.gov/media/1875389/err189.pdf

[xii] Ibid, pp. 28-29.

[xiii] Ibid, pp. 17-18.

[xiv] Ball, Eldon, Sun Ling Wang, and Richard Nehring. USDA, ERS. *Agricultural Productivity in the U.S.: Findings, Documentation, and Methods*. Washington: USDA, ERS. Updated: Monday, May 09, 2016. Retrieved from: http://www.ers.usda.gov/data-products/agricultural-productivity-in-the-us/findings,-documentation,-and-methods.aspx#majorfinding

[xv] Ibid.

[xvi] Schimmelpfennig, David. *Cost Savings from Precision Agriculture Technologies on U.S. Corn Farms.* USDA, ERS Amber Waves. May 2, 2016. Retrieved from: http://www.ers.usda.gov/amber-waves/2016-may/cost-savings-from-precision-agriculture-technologies-on-us-corn-farms.aspx#.Vz0t_Y-cHIV

[xvii] Tilman, David, Kenneth G. Cassman, Pamela A. Matson, Rosamond Naylor & Stephen Polasky. *Agricultural sustainability and intensive production practices. Nature* **418**, 671-677 (8 August 2002). Retrieved from: http://www.nature.com/nature/journal/v418/n6898/full/nature01014.html

[xviii] Krutilla, John V. *"Conservation Reconsidered."* American Economic Review, Vol. 57, Issue 4 (Sept. 1967, pp. 777-786. Retrieved from: http://www.rff.org/files/sharepoint/News/Features/Documents/071003%20Krutilla-ConservationReconsidered.pdf

[xix] Kremen, C., and A. Miles. 2012. Ecosystem services in biologically diversified versus conventional farming systems: benefits, externalities, and trade-offs *Ecology and Society* **17**(4): 40. Retrieved from: http://dx.doi.org/10.5751/ES-05035-170440

[xx] OECD (2014a), Green Growth Indicators 2014, OECD Green Growth Studies, OECD Publishing, Paris. DOI: Retrieved from: http://dx.doi.org/10.1787/9789264202030-en

[xxi] Dobermann, Achim and Rebecca Nelson, Chairs of the UN Thematic Group **on** Sustainable Agriculture and Food Systems of the Sustainable Development Solutions Network. *Solutions for Sustainable Agriculture and Food Systems: Technical Report for the Post-2015 Development Agenda.* 18 September 2013. Retrieved from: http://unsdsn.org/wp-content/uploads/2014/02/130919-TG07-Agriculture-Report-WEB.pdf

[xxii] OECD (2014), Green Growth Indicators 2014, OECD Green Growth Studies, OECD Publishing. Retrieved from: http://dx.doi.org/10.1787/9789264202030-en

[xxiii] Dobermann, Achim and Rebecca Nelson, p. 13.

[xxiv] USDA, Alternative Farming Systems Information Center (AFSIC). *Sustainability in Agriculture.* National Agricultural Library. May 2016. Retrieved from: https://afsic.nal.usda.gov/sustainability-agriculture-0

[xxv] Sands, Ron. *Economic Responses Offset Potential Climate Change Impacts on Global Agriculture.* USDA, ERS. Amber Waves, October 06, 2014. Retrieved from: http://www.ers.usda.gov/amber-waves/2014-october/economic-responses-offset-potential-climate-change-impacts-on-global-agriculture.aspx#.V1Xhg5ErK03

[xxvi] Lobell, David B., and Sharon M. Gourdji. *The Influence of Climate Change on Global Crop Productivity.* Plant Physiology: December 2012 vol. 160, no. 4, 1686-1697, American Society of Plant Biologists. Retrieved from: http://dx.doi.org/10.1104/pp.112.208298

[xxvii] Ibid.

[xxviii] Nelson, Gerald C., Hugo Valin, Ronald D. Sands, Petr Havlík, Helal Ahammad, Delphine Deryng, Joshua Elliott, Shinichiro Fujimori, Tomoko Hasegawa, Edwina Heyhoe, Page Kyle, Martin Von Lampe, Hermann Lotze-Campen, Daniel Mason d'Croz, Hans van Meijl, Dominique van der Mensbrugghe, Christoph Müller, Alexander Popp, Richard Robertson, Sherman Robinson, Erwin Schmid, Christoph Schmitz, Andrzej Tabeau, and Dirk Willenbockel. *Climate Change Effects on Agriculture: Economic Responses to Biophysical Shocks.* Proceedings of the National Academy of Sciences, Vol. 111, No. 9, pp. 3274–3279. August 2013. doi: 10.1073/pnas.1222465110. Retrieved from: http://www.pnas.org/content/111/9/3274.full

[xxix] Yang, Sansi and C. Richard Shumway. Dynamic Adjustment in US Agriculture under Climate Change. Am. J. Agr. Econ. (2016) 98 (3):910-924.doi: 10.1093/ajae/aav042. Retrieved from: http://ajae.oxfordjournals.org/content/98/3/910.full.pdf+html?sid=dfcd0105-f3c7-45a0-9547-9b542184ac7a

[xxx] Heimlich, Ralph. *Agricultural Resources and Environmental Indicators.* USDA, ERS Agriculture Handbook AH-722, Chapter 5.1, *Agricultural Productivity*, pp. 11-15. February 2003. Retrieved from: http://www.ers.usda.gov/media/873664/agproductivity.pdf

[xxxi] Fuglie, Keith, Nicole Ballenger, Kelly Day-Rubenstein, Cassandra Klotz, Michael Ollinger, John Reilly, Utpal Vasavada, and Jet Yee. *Agricultural Research and Development: Public and Private Investments under Alternative Markets and Institutions*. Agricultural Economic Report No. (AER-735) 88 pp, May 1996. Retrieved from: http://www.ers.usda.gov/publications/aer-agricultural-economic-report/aer735.aspx

[xxxii] Fuglie, Keith Keith, Nicole Ballenger, Kelly Day-Rubenstein, Cassandra Klotz, Michael Ollinger, John Reilly, Utpal Vasavada, and Jet Yee. *Public-Private Collaboration in Agricultural Research*, Agricultural Economic Report No. (AER-735), pp. 51-57, May 1996. Retrieved from: http://www.ers.usda.gov/media/463777/aer735s5_1_.pdf

[xxxiii] Ibid, pp. 53-56.

[xxxiv] Fuglie, Keith O., James M. MacDonald, and Eldon Ball. *Productivity Growth in U.S. Agriculture.* USDA, ERS Economic Brief Number 9, September 2007. Retrieved from: http://www.ers.usda.gov/media/201254/eb9_1_.pdf

[xxxv] Joerger, R. M. (2003). *Student Perspectives of the Nature, Effectiveness, and Value of the Minnesota Farm Business Management Education Program.* Journal of Agricultural Education, 44(1), p56-69. Retrieved from Charles R. Holcomb. *Producer Attitudes and Farm Management Education.* Master's Thesis, University of Minnesota Duluth, 2011.
Retrieved from: https://d-commons.d.umn.edu/bitstream/10792/148/1/Holcomb,%20Charles.pdf

[xxxvi] Munisamy, Gopinath and Terry L. Roe. *Sources of Sectoral Growth in an Economy Wide Context: The Case of U.S. Agriculture.* University of Minnesota Economic Development Center. Department of Economics, Minneapolis

Department of Applied Economics, St. Paul. Bulletin Number 95-7, August 1995. Retrieved from: http://ageconsearch.umn.edu/bitstream/7454/1/edc95-07.pdf

[xxxvii] Wang, Sun Ling, Paul Heisey, David Schimmelpfennig, and Eldon Ball. *Agricultural Productivity Growth in the United States: Measurement, Trends, and Drivers,* ERR-189, U.S. Department of Agriculture, Economic Research Service, July 2015, pp. 53-56. Retrieved from: http://www.ers.usda.gov/media/1875389/err189.pdf

[xxxviii] Ibid, p. 54.

[xxxix] Heisey, P., S.L. Wang, and K. Fuglie. 2011. *Public Agricultural Research Spending and Future U.S. Agricultural Productivity Growth: Scenarios for 2010-2050*. Economic Brief 17. U.S. Department of Agriculture, Economic Research Service. Retrieved from: www.ers.usda.gov/publications/eb-economic-brief/eb17.aspx

---

[i] Heimlich, Ralph. *Agricultural Resources and Environmental Indicators. Chapter 5: Agricultural Productivity and Research.* USDA, ERS. Agricultural Handbook 722. February 2003. http://infohouse.p2ric.org/ref/37/36628_files/AREI5-1productivity.pdf

[ii] OECD (2011), *Fostering Productivity and Competitiveness in Agriculture*, OECD Publishing. Page 25. Retrieved from: http://dx.doi.org/10.1787/9789264166820-en,

[iii] Council on Foreign Relations (CFR), Roger C. Altman, Presider "Agricultural Technology and Productivity Continue to Make Gains and Ensure U.S. Food Security: A Conversation With Tom Vilsack." CFR Events: Renewing America Series. April 9, 2014. Retrieved from: http://www.cfr.org/agricultural-policy/agricultural-technology-productivity-continue-make-gains-ensure-us-food- security/p35599

[iv] The Tornqvist index calculation technique incorporates prices from both the base period and the comparison period to determine the indexed weighted averages. A benefit of the Tornqvist method is that inputs to the production process need not be perfect substitutes.

[v] Heimlich, Ralph. *Agricultural Resources and Environmental Indicators. Chapter 5: Agricultural Productivity and Research.* USDA, ERS. Agricultural Handbook 722. February 2003. http://infohouse.p2ric.org/ref/37/36628_files/AREI5-1productivity.pdf

[vi] OECD (2014), Green Growth Indicators 2014, OECD Green Growth Studies, OECD Publishing. Retrieved from: http://dx.doi.org/10.1787/9789264202030-en

[vii] *Fallacy of Composition:* What is true for the individual is not necessarily true for the group. Samuelson, Paul and William Nordhaus. *Economics, Sixteenth Edition.* Boston: Irwin McGraw-Hill, 1998, pp. 6-7.

[viii] Cochrane, Willard W. 1958. Farm Prices. Myth and Reality. Minneapolis: University of Minnesota Press. Retrieved from: http://barrett.dyson.cornell.edu/Papers/IFPRIMay2002.pdf

[ix] Levins, Richard A. and Willard W. Cochrane. *"The Treadmill Revisited."* Land Economics. Vol. 72, No. 4 (Nov., 1996), pp. 550-553. Retrieved from: https://www.jstor.org/stable/3146915?seq=1#page_scan_tab_contents

[x] OECD (2011), *Fostering Productivity and Competitiveness in Agriculture*, OECD Publishing. Retrieved from: http://dx.doi.org/10.1787/9789264166820-en, page 25.

[xi] Ibid, p. 25.

[xii] Wang, Sun Ling, Paul Heisey, David Schimmelpfennig, and Eldon Ball. *Agricultural Productivity Growth in the United States: Measurement, Trends, and Drivers*, ERR-189, U.S. Department of Agriculture, Economic Research Service, July 2015. Retrieved from: http://www.ers.usda.gov/media/1875389/err189.pdf

[xiii] Ibid, pp. 28-29.

[xiv] Ibid, pp. 17-18.

[xv] Fuglie, Keith and Nicholas Rada. USDA-ERS. *Summary Findings: International Agricultural Productivity.* October 16, 2017. Retrieved from: https://www.ers.usda.gov/data-products/international-agricultural-productivity/summary-findings/

[xvi] Ibid.

[xvii] Ibid.

[xviii] European Commission. *Productivity in EU Agriculture – Slowly But Steadily Growing.* EU Agricultural Markets, Number 10, December 2016. Pages 10-11. Retrieved from: https://ec.europa.eu/agriculture/sites/agriculture/files/markets-and-prices/market-briefs/pdf/10_en.pdf

[xix] Ball, Eldon, Sun Ling Wang, and Richard Nehring. USDA, ERS. *Agricultural Productivity in the U.S.: Findings, Documentation, and Methods*. Washington: USDA, ERS. Updated: Monday, May 09, 2016. Retrieved from: http://www.ers.usda.gov/data-products/agricultural-productivity-in-the-us/findings,-documentation,-and-methods.aspx#majorfinding

[xx] Ibid.

[xxi] Ibid.

[xxii] Ibid.

[xxiii] Schimmelpfennig, David. *Cost Savings from Precision Agriculture Technologies on U.S. Corn Farms.* USDA, ERS Amber Waves. May 2, 2016. Retrieved from: http://www.ers.usda.gov/amber-waves/2016-may/cost-savings-from-precision-agriculture-technologies-on-us-corn- farms.aspx#.Vz0t_Y-cHIV

[xxiv] Tilman, David, Kenneth G. Cassman, Pamela A. Matson, Rosamond Naylor & Stephen Polasky. *Agricultural sustainability and intensive production practices. Nature* **418**, 671-677 (8 August 2002). Retrieved from: http://www.nature.com/nature/journal/v418/n6898/full/nature01014.html

[xxv] Ibid.

[xxvi] Krutilla, John V. *"Conservation Reconsidered."* American Economic Review, Vol. 57, Issue 4 (Sept. 1967, pp. 777-786. Retrieved from: http://www.rff.org/files/sharepoint/News/Features/Documents/071003%20Krutilla-ConservationReconsidered.pdf

[xxvii] Kremen, C., and A. Miles. 2012. *Ecosystem services in biologically diversified versus conventional farming systems: benefits, externalities, and trade-offs*. Ecology and Society **17**(4): 40. Retrieved from: http://dx.doi.org/10.5751/ES-05035-170440

[xxviii] OECD (2014a), Green Growth Indicators 2014, OECD Green Growth Studies, OECD Publishing, Paris. DOI: Retrieved from: http://dx.doi.org/10.1787/9789264202030-en

[xxix] Dobermann, Achim and Rebecca Nelson, Chairs of the UN Thematic Group **on** Sustainable Agriculture and Food Systems of the Sustainable Development Solutions Network. *Solutions for Sustainable Agriculture and Food Systems: Technical Report for the Post-2015 Development Agenda.* 18 September 2013. Retrieved from: http://unsdsn.org/wp-content/uploads/2014/02/130919-TG07-Agriculture-Report-WEB.pdf

[xxx] OECD (2014), Green Growth Indicators 2014, OECD Green Growth Studies, OECD Publishing. Retrieved from: http://dx.doi.org/10.1787/9789264202030-en

[xxxi] Dobermann, Achim and Rebecca Nelson, p. 13.

[xxxii] USDA, Alternative Farming Systems Information Center (AFSIC). *Sustainability in Agriculture.* National Agricultural Library. May 2016. Retrieved from: https://afsic.nal.usda.gov/sustainability-agriculture-0

[xxxiii] Sands, Ron. *Economic Responses Offset Potential Climate Change Impacts on Global Agriculture.* USDA, ERS. Amber Waves, October 06, 2014. Retrieved from: http://www.ers.usda.gov/amber-waves/2014-october/economic- responses-offset-potential-climate-change-impacts-on-global-agriculture.aspx#.V1Xhg5ErK03

[xxxiv] Lobell, David B., and Sharon M. Gourdji. *The Influence of Climate Change on Global Crop Productivity.* Plant Physiology: December 2012 vol. 160, no. 4, 1686-1697, American Society of Plant Biologists. Retrieved from: http://dx.doi.org/10.1104/pp.112.208298

[xxxv] Ibid.

[xxxvi] Nelson, Gerald C., Hugo Valin, Ronald D. Sands, Petr Havlík, Helal Ahammad, Delphine Deryng, Joshua Elliott, Shinichiro Fujimori, Tomoko Hasegawa, Edwina Heyhoe, Page Kyle, Martin Von Lampe, Hermann Lotze-Campen, Daniel Mason d'Croz, Hans van Meijl, Dominique van der Mensbrugghe, Christoph Müller, Alexander Popp, Richard Robertson, Sherman Robinson, Erwin Schmid, Christoph Schmitz, Andrzej Tabeau, and Dirk Willenbockel. *Climate Change Effects on Agriculture: Economic Responses to Biophysical Shocks.* Proceedings of the National Academy of Sciences, Vol. 111, No. 9, pp. 3274–3279. August 2013. doi: 10.1073/pnas.1222465110. Retrieved from: http://www.pnas.org/content/111/9/3274.full

[xxxvii] Yang, Sansi and C. Richard Shumway. Dynamic Adjustment in US Agriculture under Climate Change. Am. J. Agr. Econ. (2016) 98 (3):910-924.doi: 10.1093/ajae/aav042. Retrieved from: http://ajae.oxfordjournals.org/content/98/3/910.full.pdf+html?sid=dfcd0105-f3c7-45a0-9547-9b542184ac7a

[xxxviii] Heimlich, Ralph. *Agricultural Resources and Environmental Indicators.* USDA, ERS Agriculture Handbook AH-722, Chapter 5.1, *Agricultural Productivity*, pp. 11-15. February 2003. Retrieved from: http://www.ers.usda.gov/media/873664/agproductivity.pdf

[xxxix] Fuglie, Keith, Nicole Ballenger, Kelly Day-Rubenstein, Cassandra Klotz, Michael Ollinger, John Reilly, Utpal Vasavada, and Jet Yee. *Agricultural Research and Development: Public and Private Investments under Alternative Markets and Institutions*. Agricultural Economic Report No. (AER-735) 88 pp, May 1996. Retrieved from: http://www.ers.usda.gov/publications/aer-agricultural-economic-report/aer735.aspx

[xl] Fuglie, Keith Keith, Nicole Ballenger, Kelly Day-Rubenstein, Cassandra Klotz, Michael Ollinger, John Reilly, Utpal Vasavada, and Jet Yee. *Public-Private Collaboration in Agricultural Research,* Agricultural Economic Report No. (AER-735), pp. 51-57, May 1996. Retrieved from: http://www.ers.usda.gov/media/463777/aer735s5_1_.pdf

[xli] Ibid, pp. 53-56.

[xlii] Fuglie, Keith O., James M. MacDonald, and Eldon Ball. *Productivity Growth in U.S. Agriculture.* USDA, ERS Economic Brief Number 9, September 2007. Retrieved from: http://www.ers.usda.gov/media/201254/eb9_1_.pdf

[xliii] Joerger, R. M. (2003). *Student Perspectives of the Nature, Effectiveness, and Value of the Minnesota Farm Business Management Education Program.* Journal of Agricultural Education, 44(1), p56-69. Retrieved from Charles R. Holcomb. *Producer Attitudes and Farm Management Education.* Master's Thesis, University of Minnesota Duluth, 2011. Retrieved from: https://d-commons.d.umn.edu/bitstream/10792/148/1/Holcomb,%20Charles.pdf

[xliv] Munisamy, Gopinath and Terry L. Roe. *Sources of Sectoral Growth in an Economy Wide Context: The Case of U.S. Agriculture.* University of Minnesota Economic Development Center. Department of Economics, Minneapolis Department of Applied Economics, St. Paul. Bulletin Number 95-7, August 1995. Retrieved from: http://ageconsearch.umn.edu/bitstream/7454/1/edc95-07.pdf

[xlv] Wang, Sun Ling, Paul Heisey, David Schimmelpfennig, and Eldon Ball. *Agricultural Productivity Growth in the United States: Measurement, Trends, and Drivers*, ERR-189, U.S. Department of Agriculture, Economic Research Service, July 2015, pp. 53-56. Retrieved from: http://www.ers.usda.gov/media/1875389/err189.pdf

[xlvi] Ibid.

[xlvii] Heisey, P., S.L. Wang, and K. Fuglie. 2011. *Public Agricultural Research Spending and Future U.S. Agricultural Productivity Growth: Scenarios for 2010-2050*. Economic Brief 17. U.S. Department of Agriculture, Economic Research Service. Retrieved from: www.ers.usda.gov/publications/eb-economic-brief/eb17.aspx