RIS
Research and Information System
for Developing Countries

Asian Biotechnology and Development Review
Vol. 18 No. 1, pp 39-68

Ecosystems, Food Crops, and Bioscience: A Symbiosis for the Anthropocene

William Hoffman

Abstract: Changes in Earth's climate at the end of the last ice age brought about seasonal conditions that favoured the cultivation of annual plants like wild cereals, helping to launch the agricultural revolution. Earth's climate is changing again, mainly through the effects of human actions on the biosphere. To feed a projected population of 9.6 billion people by 2050 while reducing agriculture's carbon, nitrogen, and environmental footprints requires a revolution in food crop productivity and a deeper understanding of the interplay between sustainable food production and natural ecosystems. These goals cannot be achieved without making appropriate use of advanced technologies. Genome-wide association studies, marker-assisted selection, and genomic selection of orphan crops in developing countries can help enhance yields, nutrition, disease resistance, and crop resilience in the face of climate change. With major cereal crop yields stagnating or in decline, successful C4 photosynthesis engineering of rice and wheat and nitrogen fixation engineering of rice, wheat, and maize would have enormous consequences for crop productivity, environmental remediation, and land, soil, and water conservation. Next-generation DNA sequencing, genome editing, synthetic biology, and molecular modeling provide the tools needed for these ambitious efforts to succeed. Innovative food crop bioscience and healthy ecosystems constitute a symbiosis for the Anthropocene.

Keywords: Climate, Crops, Ecosystems, Genomics, Genome editing, Synthetic Biology

So Gilgamesh felled the trees of the forests and Enkidu cleared their roots as far as the bank of the Euphrates. – The *Epic of Gilgamesh*

The ability of human societies to modify and transform biological systems will increase more in this century than it has in the hundred centuries since the dawn of agriculture. -- *Nature*

* Department of Laboratory Medicine and Pathology at the University of Minnesota Medical School. E-mail: hoffm003@umn.edu

Introduction

Crops and climate have a long kinship. The systematic cultivation of plants for food occurred independently in various parts of the world during the early Holocene, a period of global warming that followed the end of the last ice age (Ferrio, Voltas and Araus 2011). The adoption and spread of plant and animal domestication constituted the first large-scale human inroad into natural ecosystems and laid the groundwork for the rise of complex human societies. At the regional level, Near East farming communities cleared forests for crops to take advantage of more bountiful rainfall associated with changes in atmospheric circulation (Araus *et al.* 2014; Black, Brayshaw and Rambeau 2010). In so doing, they unwittingly initiated a process that now is reaching critical mass and disrupting the only realm where life is known to exist, Earth's biosphere (Ruddiman 2003; Barnosky *et al.* 2012; Williams, M. *et al.* 2015, Waters *et al.* 2016). Yet microbial life helped to shape Earth long before *Homo sapiens* began remodeling the planet (Gross 2015). Even as we contend with biophysical disruptions of our own making, powerful new molecular tools derived from microbial life are poised to assist us in restoring Earth's natural cycles and enhancing the food plants we grow (Science 2016; Nature 2015; Doudna and Charpentier 2014; Sternberg and Doudna 2015; Voytas and Gao 2014).

Energy, Ecosystems, and Agriculture

The total amount of energy in the biosphere sets the overall conditions for life. The role of energy in ecosystem food webs was first described in the mid-twentieth century, thereby linking living things with their physical surroundings (Lindeman 1942, Odum 1953; Hoffman 2016). Since then Earth has experienced a "Great Acceleration" marked among other things by rapid growth in the human population, surging energy production and consumption and resulting greenhouse gas emissions, ocean acidification, environmental degradation, habitat fragmentation and dissolution, and the mass extinction of species (Rockström *et al.* 2009; Lewis and Maslin 2015, Steffen *et al.* 2015a). A new human-dominated geological epoch, the Anthropocene, has been proposed (Crutzen and Stoermer 2000; Crutzen 2002).[1]

The energy demand for life – for metabolism, respiration and reproduction – has not changed. The energy demand for human life, as humans prefer to live it, has changed exponentially, running up against constraints posed by ecology and thermodynamics (Brown *et al.* 2011; Barnosky *et al.* 2012; Schramski, Gattie and Brown 2015). These constraints have yet to be reflected in standard neoclassical macroeconomic growth models, delaying wider appreciation of economics as a life science as well as a social science in the Anthropocene (Arrow *et al.* 1995; Mayumi and Gowdy 1999; Brown and Timmerman 2015). The view that entropy law "is of no immediate practical importance for modeling what is, after all, a brief instant of time in a small corner of the universe" (Solow 1997)[2] is increasingly untenable. The "small corner of the universe" is undergoing a profound biophysical transformation, and economies are embedded in the biosphere (Victor and Jackson 2015). The long-term social and economic productivity costs of fossil fuel energy production and consumption are projected to mount (Rozenberg and Hallegatte 2015; Burke, Hsiang and Miguel 2015) as are environmental costs associated with the "Great Acceleration.[3] With respect to fossil fuels exploration and climate, U.S. courts are just beginning to require calculation of carbon costs for leasing of federal lands.[4]

Foods systems, which are heavily dependent on fossil fuels, consume nearly one-third of global energy supplies (FAO 2014). A framework of "planetary boundaries" has been proposed to create a "safe operating space" for humanity and prevent potentially catastrophic biophysical thresholds from being crossed (Steffen *et al.* 2004; Rockström *et al.* 2009; Steffen *et al.* 2015b). With respect to agriculture, they include climate change, biodiversity loss, disruption of the nitrogen and phosphorous cycles, and changes in land use. Climate change, biodiversity loss, and the nitrogen cycle have already crossed their proposed boundaries. A boundary of 15 percent is proposed for the percentage of global land cover converted to cropland (Rockström *et al.* 2009). It is estimated that cropland currently covers 11-12 per cent of Earth's land surface (Rockström *et al.* 2009; Foley *et al.* 2011). The total amount of cropland *per se* is less of a factor in the land-systems change boundary than the amount of forest cover sacrificed for cropland because forests, especially tropical forests, have a strong influence on climate regulation (Steffen *et al.* 2015b). In the tradeoff between carbon stocks and crop yield or "trading carbon for food," increasing yield on existing tropical croplands including through genetic innovation is preferable to clearing new land (West *et al.* 2010). Agriculture, forests, and greenhouse gas emissions are inextricably linked. The linkage offers opportunities for "climate-smart" local agricultural practises in tropical regions (FAO 2013; Carter *et al.* 2015) where deforestation for crops and pasture as well as timber proceeds apace (Kim, Sexton, and Townshend 2015) and where the human population is expected to grow faster than anywhere else in the world.[5]

Crop Yields, Climate, and Bioscience

Global food crop production grew approximately 160 per cent from 1960 to 2005, mostly by improved production on existing farmlands. The 45-year span of yield improvements largely associated with efficient management as opposed to expanding croplands at the expense of forests also served to mitigate greenhouse gas emissions (Burney, Davis and Lobell 2010).[6] But the era of unbound crop productivity growth using current technology and management practises may be drawing to a close. Today global yields of the world's major cereal crops (maize, rice, wheat) have stagnated in one-third of producing regions (Ray *et al.* 2012). Overall growth in yields of these crops plus soybean will be inadequate to double their production by 2050 to meet projected demands mainly from human population growth and diets with more meat and dairy products (Ray *et al.* 2013; Tilman and Clark 2014). Indeed, the crops needed to feed the poultry, beef and other livestock to meet projected demands for meat would require every acre of the planet's cropland, leaving no room for human plant food production (Elam 2015; Bunge 2015).

Regional climate variability (temperature and precipitation and their interaction) may explain as much as one-third of global crop yield variability for maize, rice, wheat, and soybean, which together account for about two-thirds of current harvested global crop calories (Ray *et al.* 2015). About half of global maize production is concentrated in high yielding maize belts primarily in two regions—the American Midwest and the Chinese Maize Belt (Ray *et al.* 2015). In these two regions nearly half of corresponding yield variability can be explained by variability in temperature and rainfall and the interaction between the two. Cropland is much more sensitive to extreme climatic conditions such as drought than are natural ecosystems, as measured by vegetation productivity (Ma *et al.* 2015). The 2012 drought in the American Midwest, which reduced overall maize yields to 1995 levels, was estimated to have cost the U.S. economy between $20-$77 billion.[7]

In their highly cited seminal article "Solutions for a Cultivated Planet," Foley *et al.* (2011) observe that to meet the world's future food security and sustainability needs food production must grow substantially at the same time that agriculture's environmental footprint must shrink dramatically. Agricultural expansion should be halted,consumers should shift away from meat-based diets and reduce food waste, and farmers should strive to improve the yield and resilience of cropping systems including on underperforming lands. Multiple paths exist for improving the production, food security and environmental performance of agriculture. In searching for solutions we should remain "technology-neutral" with respect to conventional agriculture, genetic modification, and organic farming (Foley *et al.* 2011). Both demand-side and supply-side emissions mitigation measures need to be implemented in agriculture, with the latter focusing on the production of more agricultural product per unit of input (Smith *et al.* 2013).

Genetic research a century ago prepared the soil for the wave of hybrid seed varieties that swept over American cropland in the 1930s. It was, in many ways, the first genetic revolution, bringing together Mendel's field research on heredity with experimental laboratory science like Morgan's fruit fly studies in the broader context of industrial growth (Allen 1979). Hybrid seed development and the Green Revolution that followed together with steady advances in agricultural mechanisation resulted in remarkable increases in food crop productivity. In recent decades, advances in molecular biology enabled plant transgenesis or the genetic modification (GM) of plant genomes through the introduction of foreign DNA to improve food crop productivity and management. In 2014, 82 per cent of soybeans growing on 111 million hectares and 30 per cent of maize growing on 184 million hectares contained one or more transgenes that provided traits such as resistance to insects or herbicides (James 2014). Worldwide, of the 1.5 billion hectares of arable land, about 12 percent were planted with GM seed in 2012. Nearly all were planted with GM soybeans, maize, cotton, and canola in five countries: the U.S., Brazil, Argentina, Canada, and India (Hoffman and Furcht 2014a).

The complex, costly, and time-intensive regulatory system in the United States discourages public-sector researchers from using molecular methods to improve crops for farmers. Thus transgenic or GM crops have been limited largely to those for which there is a large seed market such as soybeans, maize, and cotton. "Without broader research programmes outside the seed industry," editorialised *Nature*, "developments will continue to be profit-driven, limiting the chance for many of the advances that were promised 30 years ago," among them feeding the planet's growing human population in a sustainable way and reducing agriculture's environmental footprint (Nature 2013; Hoffman and Furcht, 2014a). Transgenic or GM crops have other limitations. Rather than harnessing a plant's native genetic endowment to create desired traits as in selective breeding, GM adds genetic material from another species through recombinant DNA technology. Two decades of scientific study have shown no greater risk posed by genetic modification through recombinant DNA than that posed by other forms of genetic modification (Sanchez 2015). Still, public concerns over the cultivation of crops with foreign DNA, particularly those generated by the introduction of genes from distantly related organisms, have contributed to their limited use (Voytas and Gao 2014; Wolt, Wang and Yang 2015), in the view of some to the benefit of wealthier countries and at the expense of poorer ones. Farmers in poor countries rely almost entirely on food crops that could benefit from GM, not on GM crops for animal feed or industrial use that benefit a handful of farmers in countries like the U.S. (Paarlberg 2014). Yet campaigns to connect biosafety to public concern for the vulnerability of farmers and food with the operations of ag-bio corporate monopolies have been highly successful.

Bridging the Gap Between New Science and Smallholder Farming

Five hundred years ago the Columbian Exchange linked continental ecosystems together, facilitating the global dispersion of animal, plant, microbial and human genes (Crosby 1973). The term "Homogenocene" is sometimes used to describe the ensuing era marked by the homogenisation of biosystems and ecosystems (Samways 1999).Today the genomes of most of the major domesticated animals and plants and infectious disease pathogens in the Columbian Exchange have been fully (or nearly) sequenced (Hoffman

2014). In our Genomic Exchange era, animal, plant and microbial as well as human genetic and regulatory sequences travel around the world over high-speed data networks, a profound and disruptive advance for human and animal health and future food production.

Among the plant foods exchanged between the Old World and the New World were cassava (manioc), which was domesticated in Brazil, and today is a food staple in Africa and Asia, and yams, which are native to Africa and Asia and are widely cultivated there today as well as in Oceania and the Americas. The genomes of cassava and yam have been sequenced (Wang, L. *et al.* 2014; Oli *et al.* 2016). Genomic sequencing provides valuable insights for advancing basic research, gene discovery and genomic selection-assisted breeding to introduce improved traits. Cassava and yams are examples of "orphan crops," that typically are not traded in international markets but that may be vitally important for regional food security. Small-scale farmers or smallholders in developing countries grow many orphan crops, often on marginal land. These crops receive comparatively little attention from crop breeders and research institutions. For that reason, public-sector investment is considered indispensable to orphan crop research given the limited commercial potential of these crops in global markets. As Foley *et al.* (2011) contend, significant opportunities may exist to improve yield, the resilience of cropping systems, and preserving crop diversity by improving orphan crops because by and large they have not been genetically improved (Foley *et al.* 2011).

Private philanthropy has stepped forward and is laying the groundwork for the application of agriculture biotechnology to orphan crops, which number more than 12,000 species. The African Orphan Crops Consortium (AOCC), with financial and materials support from Mars, Inc., the sequencing powerhouse BGI, the sequencing instrument powerhouse Illumina, and a host of private and non-profit partners plans to sequence, assemble and annotate the genomes of 100 traditional African food crops.[8] AOCC's long-term goal is to use the information to develop more productive, nutritious and robust varieties that can better adapt to climate change. To help reach its goal the AOCC will train several hundred plant breeders in genomics and marker-assisted selection for crop improvement. The McKnight Foundation's Collaborative Crop Research Program (CCRP) funds collaborative research between smallholder farmers, encouraging local researchers, and development practitioners to explore solutions for sustainable, local food systems.[9] Long-term CCRP funding has allowed Ethiopian and Cornell University scientists to develop the resources necessary for tef, a nutritious orphan cereal crop that is vital for feeding some 50 million people in the Horn of Africa, to benefit from the revolution in biotechnology (CALS 2007-2010). Genomic studies of tef currently underway are designed to identify molecular markers and breeding targets for enhanced productivity, climate adaptability, and abiotic stress tolerance, and to gain a better understanding of the proteins that are responsible for the human immune response to gluten (Girma *et al.* 2014; Cannarozzi *et al.* 2014). The Bill and Melinda Gates Foundation helped to fund the Global Seed Vault on the arctic Norwegian archipelago of Svalbard, which includes the genomes of some orphan crops, though a number of species important for tropical countries are not represented (Westengen, Jeppson and Guarino 2013). The International Center for Tropical Agriculture (CIAT) and the Global Crop Diversity Trust are working to remedy the problems; the CIAT genebank stores thousands of varieties of beans, cassava, and tropical forages (CIAT 2016).

Can genomics boost the productivity of orphan crops? The question constitutes the title of correspondence by scientists from India, Mexico, Australia, the U.S., and Italy published in *Nature Biotechnology* (Varshney *et al.* 2012). The authors provide an overview and appraisal of the application of association mapping or genome-wide association studies, marker-assisted recurrent selection, and genomic selection in improving yields of orphan crops in developing countries. They conclude that the impact of genomics-assisted breeding on crop development programmes in these countries remains very limited. A number of steps need to be taken to incorporate genomic science into agricultural practise with respect to orphan crops:

- Train local scientists in modern breeding technologies;
- Improve local infrastructure for accurate and relevant crop plant phenotyping;
- Provide local access to centralisedhigh-throughput genotyping and sequencing; and
- Implement appropriate phenotypic and genotypic data management systems.

Taking these steps would help to realise the potential of converting orphan crops into "genomic resource-rich crops" and could serve to separate these crops from the term "orphan" altogether (Varshney, *et al.* 2012).

Tracking Traits in the Genomic Exchange Era

When the hybrid seed revolution swept across the American Midwest in the 1930s the idea that the code of life could be extracted, read, rewritten, and edited with uncanny accuracy was still many decades away. The best geneticists could do in the laboratory was to bombard life forms with radiation and then select a desirable mutation from the resulting mutational mess. But help was on the way. As corn with hybrid vigor shot up around Ames, Iowa, a physicist – John Vincent Atanasoff at the state college there created the first of what today is an indispensable tool for genetic research all over the world – the electronic digital computer. Life may not be a genetic algorithm, but genetic algorithms and machine learning will have a lot to say about life, ecosystems, natural cycles, and food security in coming decades as the digital world ineluctably expands.

Dramatic advances in biological methods and instrumentation during the second half of the twentieth century owe much to Moore's law. In 1965, Intel's Gordon Moore made a prediction from his careful observation of an emerging trend. Moore postulated that computing would dramatically increase in power, and decrease in relative cost, at an exponential pace. Soon computer hardware and software were put to the task of deciphering the A's, T's, G's, and C's of life code in automated machines. By the turn of the century, computer-driven DNA synthesis and sequencing instruments and amplifiers together with DNA microarrays were standard equipment in basic biological and agricultural research laboratories. The power of Moore's law pushed the life sciences in new directions.

Today biology in many ways resembles an information science based on codes, signals, systems, and networks. Next-generation DNA sequencing (NGS) of whole genomes is considered a key tool for characterising crop plant genomes and connecting plant genetic resources around the world. NGS technology enables high-resolution exploration of the relationship between genotype and phenotype at the whole genome level. It accelerates discovery of genes and quantitative gene loci (QTLs), regions of the genome encompassing multiple genes that account for a significant part of the variation of a complex phenotypic trait, say a trait for yield, nutrition, seed quality, seed dormancy, plant architecture, root system pattern, pod shattering and seed dispersal pattern, disease resistance, drought or salt tolerance, or high-temperature tolerance. QTLs are typically mapped by a number of methods including linkage analysis and genome-wide association studies. QTL mapping and marker-assisted selection (MAS), which allow gene and QTL pyramiding (stacking) in both inbred and hybrid lines, are key tools for precision plant breeding (Guimarães*et al.*2007). NGS complements these approaches and may in time replace them as the cost of whole genome sequencing declines and capabilities for analysing the vast amounts of resulting genomic data are improved. NGS technologies provide genome-wide marker coverage at a very low cost per data point, enabling practitioners to assess the inheritance of the entire genome with nucleotide-level precision (Varshney, Terauchi and McCouch 2014).

The data-sharing Genomic Exchange era is applying a suite of "omics" technologies – genomics, proteomics, transcriptomics, metabolomics, microbiomics, and others – to food crop science (Benkeblia 2014). Findings are exchanged with scientists, practitioners, and gene banks and seed banks around the world. Data from agricultural research must be widely shared to have maximum impact.[10] In addition, it is critical to connect genomics and agronomic research to individuals and communities engaged in creating new crop varieties, especially locally adapted varieties. In the view of Varshney, Terauchi, and McCouch (2014), this will require a massive reorganisation of the way plant scientists are trained. Training will have to be integrated across the scientific fields of genetics, plant breeding, computer science, mathematics,engineering, biometrics and bioinformatics. Breeding programmes will have to be reorganised and cultivars as well as data will have to be widely shared. New forms of communication will need to be developed so that farmers are well informed about the availability of improved varieties, innovative crop management systems, and market trends.

The value of online information and mobile communications devices in this context cannot be exaggerated (Sylvester 2013). "Enabling smallholder farmers to grow more food and sell it in formal markets for a fair price would change life for almost every poor person in Africa," wrote former

UN Secretary General Kofi Annan and a colleague. "The keys to fixing this problem are supplying smallholders with appropriate seeds and fertiliser, providing education and training, and ensuring easy access to markets and larger economic networks. Mobile technology can help on all these fronts" (Annan and Dryden 2015). Like cassava, yams, tef and other orphan crop plants raised in rural Africa, the mobile phones of smallholders are more likely than ever to be powered by energy from the sun. Solar-powered phone chargers and charging stations are experiencing an entrepreneurial surge across the continent.

Disruptive Tools Make Their Debut

Like all endeavours involving the manipulation of life code, plant agricultural today is poised at a "technological inflection point" (Voytas and Gao 2014). Not since the birth of molecular biology has the power of technology been brought to bear on life so precisely as with genome editing. As "Solutions for a Cultivated Planet" with its action plan for food production in the Anthropocene was being written and published (Foley *et al.* 2011), scientists were investigating and assembling these powerful genomic technologies. They include zinc finger nucleases (ZFNs), transcription activator-like effector nucleases (TALENs), meganucleases, and the leader among them, the extraordinarily efficient and comparatively easy to use CRISPR/Cas9 nuclease system (Jinek *et al.* 2012). CRISPR/Cas9 has an additional advantage over the others in that it requires only a guide RNA rather than a complex protein assembly to target the nuclease to the gene of interest.

These natural and engineered nucleases allow double-stranded DNA sequences in living cells to be cut and edited precisely, letter by letter. Because the mutation created by genome editing is difficult to distinguish from one that may occur naturally, plus the fact that foreign DNA is generally not incorporated into the DNA of the cell, the US Department of Agriculture (USDA) has thus far waived regulations that apply to genetically modified organisms. Genome editing that involves DNA base and gene insertions and deletions, which are accomplished through the natural DNA repair mechanisms of homologous repair or non-homologous end joining of double-strand DNA breaks, are under USDA review. Regulatory agencies in the U.S., Europe, Canada, and other countries are wrestling with the question of whether and, if so how, to regulate a set of technologies whose effects on living cells are increasingly indistinguishable from what occurs in traditional crop plant breeding and within plant communities in the natural world (Wolt, Wang and Yang 2015; Huang *et al.* 2016).

Genome editing or genome engineering technologies are set to transform basic biological research and plant breeding. With them it is possible to first determine the DNA sequence changes that are desired in a cultivated variety and then introduce the genetic variation within plant cells precisely and rapidly. The ability to control genetic variation within crop plants precisely and efficiently without the cost and controversy surrounding transgenic or foreign DNA will overturn the way new varieties are generated (Voytas and Gao 2014). "This technology promises to change the pace and course of agricultural research," write Jennifer Doudna and Emmanuelle Charpentier, inventors of the CRISPR/Cas9 genome editing system (Doudna and Charpentier 2014). In experiments they cite, genetic edits made by the system were passed to the next generation of plants without new mutations or off-target editing, leading Doudna and Charpentier to conclude that such findings suggest internal modification of plant genomes to provide protection from disease and resistance to pests "may be much easier than has been the case with other technologies."

Heritable targeted mutations created through genome editing have been demonstrated in a number of food crop plants, among them rice, wheat, maize, barley, sorghum, potato, tomato, and Brassica (Bortesi and Fischer 2015; Wang *et al.* 2015; Lawrenson *et al.* 2015). Sweet orange is the first fruit crop to be genetically edited (Jia and Wong 2014), potentially opening the way for the development of fruit crops with superior characteristics in countries where GM crops are poorly accepted (Kanchiswamy *et al.* 2015). Already genome editing is being used in crop production in the developed world, and this technology can also be used to improve the crops that feed the burgeoning populations of developing countries (Voytas and Gao 2014).

Agri-food systems influence the nutritional quality of foods and the availability of critical nutrients to local populations (Kaput *et al.* 2015). Genome editing could facilitate the generation of food crops with higher levels of bio-available micronutrients that are frequently lacking in the diets of people in the developing world, though some are likely to remain wary of genetically bio-fortified food crops no matter what technologies are employed (Hefferon 2015). A number of food crops have been experimentally fortified using genetic modification: rice with beta-carotene, iron, and folate; maize with ascorbate; soybean with oleic acid; canola with omega-3 fatty acid; wheat with amylose; and tomato with anthocyanin. Genome editing technologies enable researchers to expand and accelerate these advances without incorporating DNA or protein from other species in the final product (Chen and Lin 2013) while eliminating detectable off-target mutations (Kleinstiver *et al.* 2016), both of which can be verified through whole genome sequencing.

Such unprecedented control over gene sequences, activation, and expression also opens the door for the development of future crops that can better withstand pests, stress, flooding, drought, higher temperatures, and that are able to grow on marginal lands. Crop plants with such traits could be created in some cases by “knocking out”(deleting) just a few nucleotides of the billions their chromosomes carry or “knocking in” (inserting) sequences that amplify certain traits. Genome editing makes it much easier to create crop plant gene knockouts, which are key to revealing gene functionand crop plant phenotype as well as potentially controlling the loci involved in complex traits. The generation of targeted, heritable gene knockouts with nucleases like ZFNs, TALENS, CRISPR/Casand superior systems almost certain to follow will greatly facilitate genetic analysis of orphan crop species as well as crops that trade in international markets (Voytas and Gao 2014). Orphan species have lagged behind in genetic research (consistent with their “orphan” designation) due in part to the complexity and cost of creating knockout individuals for study. Together with NGS genomics and other exponentially efficient technologies, genome editing may well hasten the retirement of the term “orphan crop” if allowed to do so.

Biosynthesis and Photosynthesis for the Human Age

Genome editing is the most spectacular tool in the toolbox of the emerging field of synthetic biology, a nascent discipline founded around the turn of the millennium. Synthetic biology is based on the idea that purposeful design and engineering can be employed to study cellular systems and re-create them using biological component parts to achieve improved function (Carlson 2011; Hoffman and Furcht 2014a). In brief, synthetic biology joins science and engineering to design and construct new biological parts, devices, and systems. Artificial biosystems are modeled, constructed, and iteratively tested until their performance is optimised. Unlike the "top down" reductionist approach that characterises molecular biology, pioneers of the synthetic biology envisioned "bottom up" approach that, in some manifestations, has a lot in common with the computer hacking culture.

Although they are the most important source of the primary metabolites that feed the world and their biology is relatively well understood, plants are just beginning to draw the interest of synthetic biologists (Baltes and Voytas 2015). New biological systems involving plant cells, plant physiology and reproduction, and ecology are now in their sights. Plants use the readily available nutrients, carbon dioxide and sunlight to generate an annual photosynthetic biomass production estimated to be on the order of 2o0 billion tonnes (Baltes and Voytas 2015). Engineered plant-based biosystems hold the potential not only to improve food crop productivity and reduce crop losses but also, on a larger scale, to alter photosynthesis and natural cycles in ways that benefit ecosystems and the environment. Two such projects are well underway: the effort to equip rice, which uses C3 photosynthesis, with much more efficient C4 photosynthesis found in maize, thus increasing rice biomass and reducing its water and land area needs; and the effort to equip cereal crops with nitrogen fixation capability. If cereals like rice, wheat, and maize could have the nitrogen fixation capability of soybean and other legumes, it would relieve the enormous environmental burden of nitrogen-based fertilisers, help restore the natural balance in the nitrogen cycle, and alleviate nitrogen's contribution to greenhouse gas emissions and climate change.

In their perspective "Redesigning photosynthesis to sustainably meet global food and bioenergy demand," an international team of 25 plant scientists assert that increasing the efficiency and productivity of photosynthesis in crop plants is key to meeting future food demand (Ort *et al.* 2015). Photosynthesis functions far below its biological potential, limiting crop yields. The investigators propose several targets: increasing the ability of plants to capture light and convert light energy more efficiently; increasing the ability of plants to capture and convert carbon to plant biomass; and engineering a "smart canopy" that would enable plants that interact cooperatively to maximise the potential for light harvesting and biomass production per unit of land area.

Although C4 plants comprise less than 4 per cent of global terrestrial plant species, they contribute approximately 20 per cent to global primary productivity (Ehleringer, Cerling and Helliker 1997), a profound agricultural, ecological, and atmospheric advantage. The main obstacle to reengineering C3 to C4 photosynthesis is the carboxylation enzyme RuBisCO (ribulose-1, 5-bisphosphate carboxylase/oxygenase), the planet's most abundant protein responsible for fixing nearly all the carbon in the biosphere. But evolution has structured RuBisCO to be a relatively slow-acting enzyme, limiting the ability of plant leaves to absorb direct midday sunlight. Attempts to bolster RuBisCO through protein engineering have fallen short owing to the complexity of the molecule. Alternative strategies for increasing photosynthetic efficiency based on synthetic biology and genome engineering are now feasible. Many of the key components of RuBisCO and the photosynthetic electron transport chain are encoded in the plastid genome, which can now be engineered precisely (Bock 2014). Proof-of-concept evidence exists for how targeted alterations of the nuclear and chloroplast genomes could be made, how they would serve to redesign regulatory circuits, and how these changes would scale to a whole canopy (Ort *et al.* 2015).

The leading project for reengineering photosynthesis is the international effort to transform C3 photosynthesis in rice into much more efficient C4 photosynthesis. Investigators at the International Rice Research Institute (IRRI) in the Philippines are identifying genes associated with C4 photosynthesis and related traits. They are using the CRISPR/Cas system to knock out and knock in genes to validate their function (NCBP 2015). Genome engineering and synthetic biology equip researchers with the tools to model and control DNA from the *in silico* design and *in vitro* synthesis of standardised genetic elements to the *in vivo* manipulation of host DNA and gene expression (Baltes and Voytas 2015). Establishing a C4photosynthesis pathway in rice will require not only the insertion and activation of genes and promoters critical for C4 conversion and suppression of genes that inhibit the process but the fine tuning of gene expression to optimise protein levels in keymetabolic pathways. Analysis of transcriptomic and metabolic data from rice and maize leaves is revealing molecular components of the anatomical innovations associated with C4 photosynthesis, providing a rational systems approach to the engineering of C4 photosynthesis in rice (Wang, W. *et al.* 2014).

Another ambitious international project is also aimed at improving upon evolution, not by energising a sluggish enzyme but by outfitting certain plants that lack the ability to fix atmospheric nitrogen, namely rice, wheat, and maize which together provide 60 per cent of the world's food energy intake. Besides ameliorating the environmental damage done by the large-scale production and use of nitrogen fertilisers, even a small increase in available nitrogen through engineered fixation would be beneficial for many smallholder farmers in the developing world who have limited access to nitrogen fertilisers and tend to grow crops in low nutrient conditions (Oldroyd and Dixon 2014). Two approaches are being pursued. A number of plant species including legumes depend on bacteria such as rhizobia to convert atmospheric nitrogen into compounds that plants can use to make their essential proteins. Rhizobia produce signalling molecules called nodulation (Nod) factors during the initiation of nodules on the root of legumes. A mutually beneficial relationship or symbiosis is formed when legumes take up the bacteria. The challenge is to transfer the Nod factor signalling pathway from legumes to cereals (Oldroyd and Dixon 2014; Lau *et al.* 2014; Baltes and Voytas 2015). Signalling pathways downstream of a bacterial disease-resistance receptor that were transferred from *Arabidopsis*to wheatwere functional in responding to target bacterial pathogens (Schoonbeek *et al.* 2015), suggesting that signalling pathways are conserved across distant plant phyla and can be transferred. Alternatively, rice already possesses a mycorrhizal symbiosis signalling pathway. Because this pathway has many parallels to the rhizobial signalling pathway important in nodulation, it may be possible to engineer it to perform rhizobium Nod factor signalling in rice and possibly other cereals (Sun *et al.* 2015).

A second approach to engineering nitrogen fixation relies on the fact that some bacteria carry out their own version of the Haber-Bosch industrial process for producing ammonia from nitrogen and hydrogen. They use the enzyme nitrogenase to reduce atmospheric N_2 into NH_3, a more bio-available form. By expressing nitrogenase, plants would be able to fix their own nitrogen, a more direct approach to nitrogen fixation than that by Nod factor signalling pathway transfer. The challenge is to transfer the nitrogenase enzyme from nitrogen-fixing bacteria to plant cells (Oldroyd and Dixon 2014; Lau *et al.* 2014; Baltes and Voytas 2015). Numerous nitrogenase fixation (*nif*) genes would need to be transferred into a host plant and then properly regulated for this approach to work. Using sequence-specific gene editing nucleases, these genetic elements together with their desired regulatory elements could be integrated into “safe harbor” loci within plant genomes. Or they could be integrated downstream of endogenous cereal promoters that have the desired expression characteristics (Baltes and Voytas 2015). Both Nod factor signalling transfer and *nif* genes transfer to cereals will require microbial and plant metabolic systems analysis and engineering to be optimised (Lau *et al.* 2014). Even a limited crop plant capability to fix nitrogen would be beneficial, especially for smallholder farmers in the developing world (Oldroyd and Dixon 2014).

Conclusion: A Symbiosis for the Anthropocene

Photosynthesis and nitrogen-fixation engineering are arguably the boldest molecular endeavours ever undertaken by plant scientists, with potentially the greatest consequences for food crop productivity, environmental remediation, and land, soil, and water conservation. Rice and wheat, which together feed 40 per cent of humanity, would yield an estimated 50 per cent more using less water and nitrogen if they were successfully reprogrammed with C4 pathway photosynthesis. This would enable them to fix carbon as efficiently as the C4 crop maize, the most important cereal crop in the world measured by annual metric tonnes of production (1 billion tonnes in 2013 compared to 740 million tonnes of rice and 711 million tonnes of wheat, FAOSTAT, 2016). Other C4 crops such as sorghum and millet can tolerate hotter, drier regional conditions, which are expected to become more prevalent as the planet warms. C3 crops like rice, wheat, barley, rye, and oat are generally more sensitive to heat and drought. More than three billion people worldwide depend on rice as a dietary staple; wheat is the most widely grown crop in the world and the second most important crop after rice in the developing world. Equipping these crops with the productive efficiency even approaching that of maize would be a global game-changer for food production and ecosystems health.

Cereal crops that are capable of meeting their own nitrogen needs in whole or part could significantly reduce the application and environmental impact of inorganic fertilisers. Nitrogen fertiliser application surplus and post-harvest loss also need to be brought into balance for cereal crops (Mueller *et al.* 2014). Both strategies – engineered nitrogen fixation and nitrogen fertiliser conservation enabled by information technology –should be harnessed to reduce the amount of new reactive nitrogen in the biosphere by as much as 75 percent to maintain a safe planetary boundary (Rockström *et al.* 2009). Many of the nearly 200 signatories of the 2015 United Nations Framework Convention on Climate Change (UNFCCC) Paris agreement (COP21) include nitrous oxide emissions reduction in their Intended National Determined Contributions (INDCs) to mitigate greenhouse gas emissions (UNFCCC 2015b). Agriculture is responsible for an estimated two-thirds of anthropogenic nitrous oxide emissions, which are projected to double by 2050 under a business-as-usual scenario (Davidson and Kanter 2014). Only China has specifically committed "[t]o develop technologies on biological nitrogen fixation" (China's INDC 2015). China's use of nitrogen fertilisers has surged, making agriculture the country's leading industrial polluter and persuading its leadership to accept agricultural biotechnology as a means of ameliorating the problem despite public misgivings (Hoffman and Furcht 2014b).

As Earth warms perhaps 2 degrees Celsius by 2050 compared to pre-industrial temperatures, yields of cereal crops and other food staples are projected to stagnate exactly when they need to be growing to feed an expanding human population. That is why population biologist Paul Ehrlich and ecologist John Harte contend that to feed the world in 2050"will require a global revolution" (Ehrlich and Harte, 2015). Humanity now faces severe biophysical constraints on food production. Arguments about "insufficient food" versus "inequitably distributed food," hamper efforts to achieve sustainable food security. They doubt that technological fixes will address the likely threat to future food supplies – climate disruption and call for "a revolutionary change in human society."

If technological advances can indeed make a major contribution to sustainable food production in the Anthropocene, it will be in part because of advances in mapping, sequencing, and editing the code of life. It will be because early life forms have evolved intricate and efficient tools of self-protection that humans can now access and implement to enhance food crop biomass, yield, nutrition, resistance to pests and drought, and a crop plant's ability to thrive when grown in higher temperatures and on marginal and saline soils. It will be because landrace seeds stored in gene banks harbour valuable genes for climate adaptation, genes that can inform and guide the development of climate adaptive and genetically diverse crop varieties. It will be because seemingly intractable challenges like engineering C4 photosynthesis and nitrogen fixation are within reach as the new genomic, molecular synthesis, and modeling tools are now available. And perhaps most important, if technological advances can make a major contribution to meeting sustainable food production by 2050, it will be because both the knowledge and the tools to make it possible are widely disseminated around the world.

The new agricultural biotechnologies have little recourse but to become more transparent and democratically available than those that preceded them. The initial large-scale application of molecular biology to agriculture has been tightly controlled by large corporations, limiting access by entrepreneurs and farmers alike and serving to fuel the potent anti-GMO movement. Agricultural biotechnology's first decades have hampered regulatory approval of grains, legumes, vegetables, and fruits with superior traits but smaller markets than maize, wheat, rice, and soybean. Regulatory and intellectual property regimes, both of which are under scrutiny, will be obligated to take into account the rise of the sharing economy as biology evolves as an information science – a realm of massive data, open-source software, facile genome editing, and incipient biohacking as well as proprietary biomolecular products and methods.

In the era of "trading carbon for food," familiar ways of perceiving problems and how to solve them no longer suffice. No economic sector is more susceptible to changes in climate patterns than agriculture because no other economic sector depends so much on the biophysical environment. To meet the requirements of expanded food production in concert with shrinking agriculture's environmental footprint, federal regulatory frameworks like the Coordinated Framework for the Regulation of Biotechnology, now under review in the U.S., need to be structured within larger frameworks, encompassing the planet and its boundaries for safe operating space. The UNFCCC Paris agreement recognises "the fundamental priority of safeguarding food security and ending hunger, and the particular vulnerabilities of food production systems to the adverse impacts of climate change" (UNFCCC 2015a). The practise of "climate-smart agriculture" through increased efficiencies, adaptation, and mitigation in the food-producing sector figures in the strategies of many countries to meet their INDC targets to reduce their greenhouse gas emissions.[11]

The "global revolution to feed the world" must occur in accordance with the global revolution to reduce environmental degradation. This monumental challenge cannot be met without deeper understanding of the interplay between natural ecosystems and food production. The chances that it will be met are diminished without due attention to ecosystem services that regenerate soil, purify water, and regulate climate through carbon storage in woody biomass, forest floor litter, grassland root systems, sediments and soils. The chances this challenge will be met are also diminished without making appropriate use of advanced technologies including in food plant genetics and bioengineering.

Healthy ecosystems, climate-smart agriculture, and innovative food crop bioscience in the hands of practitioners in fields, orchards, greenhouses, and gardens, constitute asymbiosis for the Anthropocene. We may imagine that in 2050 the planet will be powered largely by renewable energy and will also be capable of feeding its human inhabitants, half of them living in the tropics. What we can imagine is more important than what we know right now. Imagination is more important than knowledge, as Albert Einstein saw it. Knowledge is limited. Imagination, like a membrane with vast potential awaiting an impulse, envelops the earth.

Endnotes

1 For a description of geological evidence of human-induced environmental change to help define the Anthropocene as a potential geological time unit, see Waters *et al.* 2014 and Waters *et al.* (2016). See also the website for the Working Group on the 'Anthropocene' of the Subcommission on Quarternary Stratigraphy at http://quaternary.stratigraphy.org/workinggroups/anthropocene/.

2 The writings of Nobel economist Robert W. Solow represent perhaps one the most illuminating treatments of natural resource and environmental sustainability from the standpoint of mainstream macroeconomics and economic growth. In his lecture "The Economics of Resources or the Resources of Economics" (Solow 1974), Solow emphasises that the fundamental principle of the economics of exhaustible resources is "a condition of competitive equilibrium in the sequence of futures markets for deliveries of the natural resource," a sequence that "extends to infinity." The resource-exhaustion problem must depend on two aspects of technology: first, the likelihood of technical progress, especially progress that saves natural resources, and second, the ease with which other factors of production, labour and capital in particular, can be substituted for natural resources in production. Technical progress and substitutability will offset natural resource depletion. In his paper "Sustainability: An Economist's Perspective" (Solow 1993), Solow considers sustainability (in his view a "vague

concept") as "a matter of distributional equity between the present and the future" and therefore a problem about saving and investment, "a choice between current consumption and providing for the future." It would help if governments made "a comprehensive accounting of rents on non-renewable resources." A scarcity rent isthe marginal opportunity cost imposed on future generations by extracting one more unit of a resource today. Solow's comment that entropy law "is of no immediate practical importance for modeling what is, after all, a brief instant of time in a small corner of the universe" (Solow 1997) is from a collection of articles written as a tribute to the pioneering ecological economist Nicholas Georgescu-Roegen, author of *The Entropy Law and the Economic Process* (Mayumi and Gowdy 1999). Georgescu-Roegen and his successors contend that entropy law is increasingly coming into play with human population growth and the resulting "Great Acceleration" of environmental and biophysical consequences (see for example, Brown *et al.* 2011; Barnosky *et al.* 2012). Much of the debate turns on whether energy is just an input like other [economic] inputs (Krugman 2014) or whether standard economic equilibrium conditions fail to account adequately for the thermodynamic constraints of energy conversion (Kümmel and Lindenberger 2014). Energy production and consumption at present scale endanger critical complex ecosystem services whose substitutability by technical advances may not be feasible, a factor Solow does not take into account in his analysis (Sá Earp and Romeiro 2015).

3 The costs of environmental management, decline and degradation should be taken into account in measuring national wealth. In 2012, the UN University's International Human Dimensions Programme on Global Environmental Change (UNU-IHDP) and the UN Environment Programme (UNEP) jointly launched the Inclusive Wealth Index (IWI), a sustainability index that goes beyond traditional economic and development indices such as gross domestic product (GDP). Economic growth should mean growth in wealth, which is the social worth of economy's entire stock of capital assets including the typically underestimated value of natural capital embodied in natural resources and ecosystem goods and services (Dasgupta 2014). Two IWI reports have been issued (UNU-IHDP and UNEP 2012; UNU-IHDP and UNEP 2014). The 2014 IWI report, which covers 140 countries from 1990 to 2010, describes its goal as an effort to cement the role of the IWI as "the leading comprehensive indicator for measuring nations' progress on building and maintaining inclusive wealth – a central pillar of the sustainability agenda – and gauging global sustainability as part of the post-2015 development agenda as outlined in the [UN's] Sustainable Development Goals."

4 In 2014 Judge R. Brook Jackson of the U.S. District Court for the District of Colorado faulted federal agencies for failing to calculate the social cost of greenhouse gas (GHG) emissions on the basis that such a calculation was not feasible (*High Country Conservation Advocates v. U.S. Forest Service* 2014). High Country is the first case to set aside an agency's decision for its failure to consider appropriately its effect on climate. Jackson ruled that it was arbitrary and capricious for agencies to proclaim the benefits of mineral leasing that involved expansion of coal mining exploration on federal land while ignoring the costs, which in his view could be calculated using the federal government's social costs of carbon (SCS) protocol (see Executive Order 12866, 2010). The White House Council on Environmental Quality (CEQ), which coordinates federal environmental efforts, regards the SCS estimate as a tool to monetize costs and benefits and that available quantitative GHG estimation tools should help guide federal

agency analysis and decisions (CEQ 2014; Ore 2013).

5 Stateofthetropics.org

6 Burney, Davis and Lobell (2010) suggest that the climatic impacts of historical agricultural intensification were preferable to those of a system with lower inputs that instead expanded cropland to meet global food demand and that "enhancing crop yields is not incompatible with a reduction of agricultural inputs in many circumstances." They acknowledge that yield gains alone do not necessarily preclude expansion of cropland and that agricultural intensification must be coupled with conservation and development efforts. Phelps *et al.* (2013) argue that agricultural intensification, which has become central to Reducing Emissions from Deforestation and forest Degradation (REDD+) policies across the tropics, actually escalates future conservation costs and may serve to accelerate deforestation in tropical regions. The UNFCC Paris Agreement (UNFCCC, 2015a) "[r]ecognises the importance of adequate and predictable financial resources, including for results-based payments, as appropriate, for the implementation of policy approaches and positive incentives for reducing emissions from deforestation and forest degradation, and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks…." [I. Adoption, no. 55] The agreement also calls for "[i]ncreasing the ability to adapt to the adverse impacts of climate change and foster climate resilience and low greenhouse gas emissions development, in a manner that does not threaten food production…." [ANNEX, Article 2: 1b]

7. The 2012 drought in the American Midwest was the most severe and extensive drought in at least the previous quarter century, affecting three-quarters of U.S. maize and soybean production and reducing maize yields 13 per cent to 1995 levels (USDA 2012; USDA 2013). The drought was estimated to have cost the U.S. economy between $20-$77 billion (Munich Re = $20 billion, Aon Benfield = $35 billion, Morgan Stanley = $50 billion, Purdue economist = $77), which would rank it among the costliest natural disasters in U.S. history (Svoboda 2013; Keen 2012; Larsen 2015). Crop indemnities alone were estimated to be $20 billion (Svoboda 2013). Although natural climate fluctuations are thought to be primarily responsible for the 2012 drought (Mallya *et al.*2013), anthropogenic warming tends to exacerbate these natural variations (Williams, A. P. *et al*. 2015) and may reduce average annual maize yields 15 per cent in the U.S. by 2050 (Burke and Emerick 2016). Globally, drought reduced maize, rice, wheat production an estimated 9-10 percent during the period 1964-2007, with developed countries experiencing disproportionate damage (Lesk, Rowhani and Ramankutty 2016).

8 Africanorphancrops.org

9 CCRP.org

10 See, for example, DivSeek at Divseek.org and the GODAN Initiative at Godan.info

11 See McArthur (2015) and the UNFCCC's Intended Nationally Determined Contributions (INDC) database at http://unfccc.int/focus/indc_portal/items/8766.php. Emissions reductions for agriculture are not specified for large advanced producers like Australia, Canada, and the United States. In contrast, the European Union does specify areas within agriculture for emissions reduction, though how those emissions will be measured is not clear. India, which produces the world's second-largest volume of agricultural emissions, after China, is alone with China in proposing agricultural biotechnology as a tool to achieve its emission reduction goals. Its National Mission on Sustainable Agriculture strategy aims at enhancing food security and protection of resources including biodiversity and genetic resources. The mission "focuses on

new technologies and practices in cultivation, genotypes of crops that have enhanced CO_2 fixation potential, which are less water consuming and more climate resilient."In the private sector, large seed companies are beginning to respond to the international consensus. Monsanto announced its commitment to a carbon-neutral footprint across its operations by 2021 (Salter 2015).

References

Allen, G. E. 1979. *Thomas Hunt Morgan, The Man and His Science*. Princeton, NJ: Princeton University Press.

Annan, K. and S. Dryden. 2015. "Food and the Transformation of Africa: Getting Smallholders Connected." *Foreign Affairs*, 16 October. Available at: https://www.foreignaffairs.com/articles/africa/2015-10-16/food-and-transformation-africa

Araus, J. L., J. P. Ferrio, J. Voltas, M. Aguilera and R. Buxo. 2014. "Agronomic Conditions and Crop Evolution in Ancient Near East Agriculture." *Nature Communications*, 5:3953. doi: 10.1038/ncomms4953.

Arrow, K. *et al.* 1995. "Economic Growth, Carrying Capacity, and the Environment." *Science*, 268: pp. 520-521. doi:10.1126/science.268.5210.520.

Baltes, N. J. and D. F. Voytas. 2015. "Enabling Plant Synthetic Biology Through Genome Engineering." *Trends in Biotechnology*, 33(2): pp. 120-131.doi: http://dx.doi.org/10.1016/j.tibtech.2014.11.008.

Barnosky, A. D. *et al.* 2012. "Approaching a State Shift in Earth's Biosphere." *Nature*, 486: pp. 52-58. doi:10.1038/nature11018.

Benkeblia, N. (ed.). 2014. *Omics Technologies and Crop Improvement*. Boca Raton, FL: CRC Press.

Black, E., D. J. Brayshaw and C. M. C. Rambeau. 2010. "Past, Present, and Future Precipitation in the Middle East: Insights from Models and Observations." *Philosophical Transactions of the Royal Society*, A 368: pp. 5173-5184.doi: 10.1098/rsta.2010.0199.

Bock, R. 2014. "Genetic Engineering of the Chloroplast: Novel Tools and New Applications." *Current Opinion in Biotechnology*, 26: pp. 7-13. http://dx.doi.org/10.1016/j.copbio.2013.06.004.

Bono, J. M., E. C. Olesnicky and L. M. Matzkin. 2015. "Connecting Genotypes, Phenotypes and Fitness: Harnessing the Power of CRISPR/Cas9 Genome Editing." *Molecular Ecology*, 24: pp. 3810-3822. doi:10.1111/mec.13252.

Bortesi, R. and R. Fischer. 2015. "The CRISPR/Cas9 System for Plant Genome Editing and Beyond." *Biotechnology Advances*, 33: pp. 41-52. doi:10.1016/j.biotechadv.2014.12.006.

Brown, J. H. *et al.* 2011. "Energetic Limits to Economic Growth." *BioScience*,61: pp. 19–26. doi:10.1525/bio.2011.61.1.7.

Brown, P. G. and P. Timmerman. 2015. *Ecological Economics for the Anthropocene*. New York: Columbia University Press.

Bunge, J. 2015. "How to Satisfy the World's Surging Appetite for Meat." *Wall Street Journal*, December 4, 2015. Available at: http://www.wsj.com/articles/how-to-satisfy-the-worlds-surging-appetite-for-meat-1449238059.

Burke, M., S. M. Hsiang and E. Miguel. 2015. "Global Non-linear Effect of Temperature on Economic Production." *Nature*, 527: pp. 235-239. doi:10.1038/nature15725.

Burke, M. and K. Emerick. 2016. "Adaptation to Climate Change: Evidence from U.S. Agriculture." *American Economic Journal: Economic Policy*. In press.

Burney, J. A., S. J. Davis and E. B. Lobell. 2015. "Greenhouse Gas Mitigation by Agricultural Intensification." *Proceedings of the National Academy of Science U.S.A*., 107(26): pp. 1252-1257. doi: 10.1073/pnas.0914216107.

CALS (College of Agriculture and Life Sciences, Cornell University). 2007-2010. "Improving Tef in Ethiopia by Providing Researchers Access to the Benefits of Molecular Markers." Available at: http://impact.cals.cornell.edu/project/improving-tef-ethiopia-providing-researchers-access-benefits-molecular-markers.

Cannarozzi, G. *et al.* 2014. "Genome and Transcriptome Sequencing Identifies Breeding Targets in the Orphan Crop Tef (*Eragrostistef*)." *BMC Genomics*, 15 (581).

doi:10.1186/1471-2164-15-581.

Carlson, R. H. 2011. *Biology Is Technology: The Promise, Peril, and New Business of Engineering Life*. Cambridge, MA: Harvard University Press.

Carter, S. *et al.* (2015). "Mitigation of Agricultural Emissions in the Tropics: Comparing Forest Land-sparing Options at the National Level." *Biogeosciences*,12: pp. 4809–4825. doi:10.5194/bg-12-4809-2015.

CEQ (U.S. Council on Environmental Quality). 2014.Revised Draft Guidance on the Consideration of Greenhouse Gas Emissions and the Effects of Climate Change in NEPA Reviews. The White House, 18 December. Available at: https://www.whitehouse.gov/administration/eop/ceq/initiatives/nepa/ghg-guidance.

Chen, H. and Y. Lin. 2013. "Promise and Issues of Genetically Modified Crops." *Current Opinion in Biology*, 16 (2): pp. 255-260. doi: 10.1016/j.pbi.2013.03.007.

China's INDC (Intended Nationally Determined Contributions). 2015. Submitted to the United Nations Framework Convention on Climate Change (UNFCCC), submitted on 30 June. Available at: http://unfccc.int/focus/indc_portal/items/8766.php

CIAT (Centro Internacional de Agricultura Tropical). 2016. "Beans, Cassava, and Tropical Forages." Available at: https://www.croptrust.org/wp-content/uploads/Centro Internacional de Agricultura Tropical2014/12/CIAT.pdf

Crosby, A.W. 1973. *The Columbian Exchange: Biological and Cultural Consequences of 1492*. Westport, CT: Greenwood Press.

Crutzen, P. J. and E. F. Stoermer. 2000. "The Anthropocene." *Global Change Newsletter*, 41: pp. 17-18.

Crutzen, P. J. 2002. "Geology of Mankind." *Nature*, 415: pp. 23-23.

Dasgupta, P. 2014. "Measuring the Wealth of Nations." *Annual Review of Resource Economics*, 6 (1): pp. 17-31.

Davidson, E. A. and D. Kanter. 2014. "Inventories and Scenarios of Nitrous Oxide Emissions." *Environmental Research Letters*, 9 (10): 105012. doi:10.1088/1748-9326/9/10/105012.

Doudna, J.A. and E. Charpentier. 2014. "The New Frontier of Genome Engineering with CRISPR-Cas9." *Science*, 346 (6213): 1258096. doi: 10.1126/science.1258096.

Ehleringer, J. R., T. E. Cerling and B. R. Helliker. 1997. "C4 Photosynthesis, Atmospheric CO_2 and Climate." *Oecologia*, 112: pp. 285–299. doi:10.1007/s004420050311

Ehrlich, P. and J. Harte. 2015. "Opinion: To Feed the World in 2050 Will Require a Global Revolution." *Proceedings of the National Academy of Science U.S.A.*, 112(48): pp. 14743-14744. doi:10.1073/pnas.1519841112.

Elam, T. E. 2015 "Projections of Global Meat Production Through 2050." Center for Global Food Issues. Available at: http://www.farmecon.com/Pages/ArticlesandPublications.aspx.

Executive Order 12866. 2010. Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis. The White House, February 2010. Available at: https://www.whitehouse.gov/sites/default/files/omb/inforeg/for-agencies/Social-Cost-of-Carbon-for-RIA.pdf.

FAO (Food and Agriculture Organisation of the United Nations). 2013. Climate-Smart Agriculture Sourcebook. Rome, Italy. Available at: http://www.fao.org/docrep/018/i3325e/i3325e00.htm.

FAO (Food and Agriculture Organisation of the United Nations). 2014. *FAO and the Post-2015 Development Agenda: 100 Facts in 14 Themes Linking People, Food, and the Planet.* Rome, Italy. Available at: http://www.fao.org/fileadmin/user_upload/mdg/100_facts/100facts_EN.pdf

Ferrio, J. P., J. Voltas and J. L. Araus. 2011. "Global Change and the Origins of Agriculture" in J. L. Araus and G. L. Salfer (eds.). *Crop Stress Management and Global Climate Change*, pp. 1-14. Oxfordshire, UK: CABI.

Foley, J.A., *et al.* 2011. "Solutions for a Cultivated Planet." *Nature,* 478: pp. 337-342. doi:10.1038/nature10452.

Girma, D., K. Assefa, S. Chanyalew, G. Cannarozzi, C. Kuhllemeier and Z. Tadele. 2014. "The Origins and Progress of Genomics Research on Tef (Eragrostistef)." *Plant Biotechnology Journal*, 12: pp. 534-540. doi: 10.1111/pbi.12199.

Gross, M. 2015. "How Life Shaped Earth." *Current Biology,* 25: pp. R845–R875.

Guimarães, E. P., J. Ruane, B. Scherf, A. Sonnino and J. Dargie (eds.). 2007. *Marker-assisted Selection:Current Status and Future Perspectives in Crops, Livestock, Forestry and Fish*. Rome: Food and Agriculture Organization of the United Nations.

Hefferon, K. L. 2015. "Nutritionally Enhanced Food Crops: Progress and Perspectives." *International Journal of Molecular Sciences*, 16: pp. 3895-3914. doi:10.3390/ijms16023895.

High Country Conservation Advocates v. U.S. Forest Service. 2014. No. 13-cv-01723-RBJ (D. Colo. June 27, 2014).

Hoffman, W. 2014. "The Shifting Currents of Bioscience Innovation." *Global Policy*, 5 (1): pp. 76-84. doi: 10.1111/1758-5899.12108.

Hoffman, W. 2016. "Raymond Lindeman, a Bog Lake, and the Birth of Ecosystems Ecology" in A. Amato (ed.) *Conserving Conservation*. The Center for Western Studies, Augustana College, Sioux Falls.

Hoffman, W. and L. Furcht. 2014a. *The Biologist's Imagination: Innovation in the Biosciences*. New York: Oxford University Press.

Hoffman, W. and L. Furcht. 2014b. "Divergence, Convergence, and Innovation: East-West Bioscience in an Anxious Age." *Asian Biotechnology and Development Review*, 16 (3): pp. 3-23. Available at: http://www.ris.org.in/images/RIS_images/pdf/ABDR%20 Nov-2014.pdf.

Huang, S., D. Weigel, R. N. Beachy and J. Li. 2016. "A Proposed Regulatory Framework for Genome-Edited Crops." *Nature Genetics*, 48(2): pp. 109-111. doi:10.1038/ng.3484.

James, C. 2014. "Global Status of Commercialized Biotech/GM Crops: 2014." ISAAA Brief No. 49. Ithaca, NY: ISAAA.

Jia, H. and N. Wang. 2014. "Targeted Genome Editing of Sweet Orange Using Cas9/sgRNA." *PLOS One*,9(4): e93806. doi:10.1371/journal.pone.0093806.

Jinek, M. *et al.* 2012. "A Programmable Dual-RNA–Guided DNA Endonuclease in Adaptive Bacterial Immunity." *Science*, 337: pp. 816-21. doi: 10.1126/science.1225829.

Kanchiswamy, C. N., D. J. Sargent, R. Velasco, M. E. Maffei and M. Malnoy. 2015. "Looking Forward to Genetically Edited Fruit Crops." *Trends in Biotechnology*, 33 (2): pp. 62-64. doi: http://dx.doi.org/10.1016/j.tibtech.2014.07.003.

Kaput J., M. Kussmann, Y. Mendoza, R. Le Coutre, K. Cooper and A. Roulin. 2015. "Enabling Nutrient Security and Sustainability Through Systems Research." *Genes and Nutrition*, 10 (12): pp. 1-12.doi: 10.1007/s12263-015-0462-6.

Keen, J. 2012. "Midwest Drought Belt: A Changed World Emerges." *USA Today*, Sept. 20, 2012.

Kim, D-H, J. O. Sexton and J. R. Townshend. 2015. "Accelerated Deforestation in the Humid Tropics from the 1990s to the 2000s." *Geophysical Research Letters*, 42: pp. 3495-3501.

Kleinstiver, B.P., V. Pattanayak, M. S. Prew, S. Q. Tsai, N. T. Nguyen, Z. Zheng and J. K. Joung. 2016. "High-Fidelity CRISPR–Cas9 Nucleases With No Detectable Genome-wide Off-target Effects." *Nature*, 590: pp. 490-495.doi:10.1038/nature16526.

Krugman, P. 2014. "Slow Steaming and the Supposed Limits to Growth." Paul Krugman's blog, Oct. 7, 2014. Available at: http://krugman.blogs.nytimes.com/2014/10/07/slow-steaming-and-the-supposed-limits-to-growth/.

Kümmel R. and D. Lindenberger. 2014. "How Energy Conversion Drives Economic Growth Far From the Equilibrium of Neoclassical Economics." *New Journal of Physics*, 16: 125008. doi:10.1088/1367-2630/16/12/125008.

Larsen, J. 2015. "Warmest Decade on Record Brings Record Temperatures and Weather Extremes." World Resources *SIM*Center, Global Energy Network Institute. Available at: http://www.wrsc.org/story/warmest-decade-record-brings-record-temperatures-and-weather-extremes.

Lau, W., M.A. Fischbach, A. Osbourn and E.S. Satterly. 2014. "Key Applications of Plant Metabolic Engineering." *PLOS Biology,* 12(6): e1001879.

Lawrenson, T. *et al*. 2015. "Induction of Targeted, Heritable Mutations in Barley and *Brassica oleracea* Using RNA-guided Cas9 Nuclease." *Genome Biology*,16:258. doi:10.1186/s13059-015-0826-7.

Lesk C., P. Rowhani and N. Ramankutty. 2016. "Influence of Extreme Weather Disasters on Global Crop Production." *Nature*, 529:84-87. doi:10.1038/nature16467.

Lewis, S. L. and M. A. Maslin. 2015. "Defining the Anthropocene. *Nature*, 519: pp. 171-180. doi:10.1038/nature14258.

Lindeman, R. L. 1942. "The Trophic-Dynamic Aspect of Ecology." *Ecology*, 23(4): pp. 399-417.

Lowder, L. G. *et al.* 2015. "A CRISPR/Cas9 Toolbox for Multiplexed Plant Genome Editing and Transcriptional Regulation." *Plant Physiology*, 169: pp. 971-985. doi:http://www.plantphysiol.org/cgi/doi/10.1104/pp.15.00636

Ma, X., A. Huete, S. Moran, G. Ponce-Campos and D. Eamus. 2015. Abrupt Shifts in Phenology and Vegetation Productivity Under Climate Extremes. *Journal of Geophysical Research: Biogeosciences*,120(10): pp. 2036-2052.doi: 10.1002/2015JG003144.

Mallya G., L. Zhao, X. C. Song, D. Niyogi and R. S. Govindaraju. 2013. "2012 Midwest Drought in the United States." *Journal of Hydrologic Engineering*, 18(7): pp. 737-745.

Mayumi, K. and J. M. Gowdy. 1999. *Bioeconomics and Sustainability: Essays in Honor of Nicholas Georgescu-Roegen*. Cheltenham, UK: Elgar Monographs.

McArthur, J.W. 2015. "Agriculture in the COP21 Agenda." Global Economy and Development, Brookings Institution. Available at: http://www.brookings.edu/~/media/Research/Files/Reports/2015/11/16-paris-climate-talks/agriculture-in-cop21.pdf.

Mueller, N.D., P. C. West, J. S. Gerber, G. K. MacDonald, S. Polansky and J. A. Foley. 2014. "A Tradeoff Frontier for Global Nitrogen Use and Cereal Production."*Environmental Research Letters*, 9: 054002. doi:10.1088/1748-9326/9/5/054002.

Nature. 2013. "Fields of Gold." Editorial, *Nature*, 497: pp. 5-6. doi:10.1038/497005b.

Nature. 2015. "CRISPR: The Good, the Bad, and the Unknown." *Nature* Special. Available at: http://www.nature.com/news/crispr-1.17547NCBP (National Committee on Biosafety of the Philippines). 2015. Approved Experiments. Reference No. 20150294. Project Title:Validation of Function of Genes Associated with C4 Photosynthesis and Other Related Traits Through CRISPR/Cas9 System. Date of Approval: 23-05-2015. Available at: http://dost-bc.dost.gov.ph/approved-experiments/details/1/55?

Odum, E. P. 1953. *Fundamentals of Ecology*. Philadelphia: W. B. Saunders Company.

Oldroyd, G. E. D. and Dixon, R. 2014. "Biotechnological Solutions to the Nitrogen Problem." *Current Opinion in Biotechnology*, 26:19–24. http://dx.doi.org/10.1016/j.copbio.2013.08.006.

Oli, M. T. *et al.* 2016. "Whole Genome Sequencing of White Guinea Yam (*Dioscorearotundata*): Towards Generating Generating Genetic and Genomic Tools for Improvement of an African 'Orphan' Crop." Plant and Animal Genome Conference XXIV, San Diego, CA, 13 January. Abstract available at: https://pag.confex.com/pag/xxiv/webprogram/Paper20791.html.

Ore, K. S. 2013. "*High Country Conservation Advocates v. United States Forest Service*, 52 F. Supp. 3d 1174 (D. Colo. 2014)," *Public Land and Resources Law Review*: Vol. 0, Issue 6, Article 3. Available at: http://scholarship.law.umt.edu/plrlr/vol0/iss6/3

Ort, D. R. *et al.* 2015. "Redesigning Photosynthesis to Sustainably Meet Global Food and Bioenergy Demand." *Proceedings of the National Academy of Science U.S.A.,*112(28): pp. 8529-8536. doi:10.1073/pnas.1424031112.

Paarlberg, R. 2014. "A Dubious Success: the NGO Campaign Against GMOs."*GM Crops Food*, 5(3): pp. 223-238. doi:10.4161/21645698.2014.952204.

Phelps, J., L. R. Carrasco, E. L. Webb, L. P. Koh and U. Pascual. 2013, "Agricultural Intensification Escalates Future Conservation Costs." *Proceedings of the National Academy of Science U.S.A*., 110(19): pp. 7601-7606. doi:10.1073/pnas.1220070110.

Ray, D.K., N.D. Mueller, P.C. West and J.A. Foley. 2013. "Yield Trends Are Insufficient toDouble Global Crop Production by 2050." *PLOS One*, 19 June. doi: 10.1371/journal.pone.0066428.

Ray, D.K., N. Ramankutty, N.D. Mueller, P.C. West and J.A. Foley. 2012. "Recent Patternsof Crop Yield Growth and Stagnation." *Nature Communications*, 3:1293. doi:10.1038/ncomms2296.

Ray, D. K., J. S. Gerber, G. K. MacDonald, and P. C. West. 2015. "Climate Variation Explains a Third of Global Crop Yield Variability." *Nature Communications*, 6:5989. doi: 10.1038/ncomms6989.

Rockström, J. *et al.* 2009. "A Safe Operating Space for Humanity." *Nature*, 461(24): pp. 472-475.

Rogers, C. and G.E.D. Oldroyd. 2014. "Synthetic Biology Approaches to Engineering the Nitrogen Symbiosis in Cereals." *Journal of Experimental Botany,* 65(8): pp. 1939-1946. doi: 10.1093/jxb/eru098.

Rozenberg J. and S. Hallegatte. 2015. "The Impacts of Climate Change on Poverty in 2030 and the Potential from Rapid, Inclusive, and Climate-Informed Development." World Bank, Policy Research Working Paper 7483. World Bank Group.

Ruddiman, W. F. 2003. "The Anthropogenic Greenhouse Era Began Thousands of Years Ago." *Climate Change*, 61: pp. 261-293. doi:10.1023/B:CLIM.0000004577.17928.

Sá Earp, H. and A. Romeiro. 2015."The Entropy Law and the Impossibility of Perpetual Economic Growth."*Open Journal of Applied Sciences*, 5:pp. 641-650. doi:10.4236/ojapps.2015.510063.

Salter, J. 2015. "Monsanto Pledges to be Carbon Neutral by 2021." Associated Press, Dec. 1, 2015. Available at: http://bigstory.ap.org/article/b5927b75316d4ca88e5d00f9419e40c3/monsanto-pledges-be-carbon-neutral-2021.

Samways, M. 1999. "Translocating Fauna to Foreign Lands: Here Comes the Homogenocene." *Journal of Insect Conservation,* 3(2): pp. 65–66.

Sanchez, M.A. 2015. "Conflict of Interests and Evidence Base for GM Crops Food/Feed Safety Research." *Nature Biotechnology,* 33(2): pp. 135-136. doi:10.1038/nbt.3133.

Schoonbeek, H.-j. *et al.* 2015. "Arabidopsis EF-Tu Receptor Enhances Bacterial Disease Resistance in Transgenic Wheat." *New Phytologist*, 226(2): pp. 606-613. doi:10.1111/nph.13356.

Schramski, J. R., D. K. Gattie and J. H. Brown. 2015. "Human Domination of the Biosphere: Rapid Discharge of the Earth-space Battery Foretells the Future of Humankind." *Proceedings of the National Academy of Science U.S.A.,* 112(31): pp. 9511-9517. doi/10.1073/pnas.1508353112.

Science. 2016. "The CRISPR Revolution." *Science*/AAAS Special Collection. Available at: http://www.sciencemag.org/site/extra/crispr/.

Smith, P. *et al.* 2013. "How Much Land-based Greenhouse Gas Mitigation Can Be Achieved Without Compromising Food Security and Environmental Goals?" *Global Change Biology*, 19(8): pp. 2285-2302. doi:10.1111/gcb.12160.

Solow, R. W. 1974. "The Economics of Resources or the Resources of Economics." *American Economic Review*, 62(2): pp. 1-14.

Solow, R. W. 1993. "Sustainability: An Economist's Perspective" in Robert Dorfman and Nancy S. Dorfman (eds.) *Economics of the Environment: Selected Readings*, pp. 179-187. New York: W. W. Norton.

Solow, R. W. 1997. "Reply: Georgescu-Roegen versus Solow/Stiglitz." *Ecological Economics*, 22: pp. 267-268.

Steffen, W. *et al.* 2004. "Global Change and the Earth System: A Planet Under Pressure." The IGBP Global Change Series. Berlin: Springer-Verlag.

Steffen W. *et al.* 2015a. "Planetary Boundaries: Guiding Human Development on a Changing Planet." *Science*, 347(622): 1259855.doi: 10.1126/science.1259855.

Steffen W., W. Broadgate, L. Deutsch, O. Gaffney and C. Ludwig. 2015b. "The Trajectory of the Anthropocene: The Great Acceleration."*The Anthropocene Review*, 2(1): pp. 81-98.doi: 10.1177/2053019614564785.

Sternberg, S. H. and J. A. Doudna. 2015. "Expanding the Biologist's Toolkit with CRISPR-Cas9."*Molecular Cell*, 58(4): pp. 568–574. doi: http://dx.doi.org/10.1016/j.molcel.2015.02.032.

Sun, J. *et al.* 2015. "Activation of Symbiosis Signaling by ArbuscularMycorrhizal Fungi in Legumes and Rice."*The Plant Cell*, 27(3): pp. 823-838. doi:http://dx.doi.org/10.1105/tpc.114.131326.

Svoboda, M. 2013. Impacts: The Face of Drought: 2012 Drought Recap. National Drought Mitigation Center. Available at: http://www.westernstateswater.org/wp-content/uploads/2013/05/Svoboda.pdf.

Sylvester, G. (ed) 2013. *Information and Communications Technologies for Sustainable Agriculture*. FAO, Rome, Italy. Available at: http://www.fao.org/docrep/019/i3557e/i3557e.pdf

Tilman D. and M. Clark. 2014. "Global Diets Link Environmental Sustainability and Human Health." *Nature*, 515: pp. 518-522. doi:10.1038/nature13959.

UNFCC (United Nations Framework Convention on Climate Change). 2015a. Conference of the Parties, Twenty-first session. Adoption of the Paris Agreement. December 15, 2015. Available at: http://newsroom.unfccc.int/paris/.

UNFCC (United Nations Framework Convention on Climate Change). 2015b. "Synthesis Report on the Aggregate Effect of the Intended Nationally Determined Contributions." Conference of the Parties, Twenty-first session, Paris, 30 November to 11 December 2015. Available at: http://unfccc.int/resource/docs/2015/cop21/eng/07.pdf.

UNU-IHDP and UNEP. 2012. *Inclusive Wealth Report 2012: Measuring Progress Toward Sustainability*. Cambridge, UK: CambridgeUniversity Press.

UNU-IHDP and UNEP. 2014. *Inclusive Wealth Report 2014: Measuring Progress Toward Sustainability.* Cambridge, UK: CambridgeUniversity Press.

USDA (U. S. Department of Agriculture). 2012. "U.S. Drought 2012: Farm and Food Impacts." Available at:http://www.ers.usda.gov/topics/in-the-news/us-drought-2012-farm-and-food-impacts.aspx.

USDA (U. S. Department of Agriculture). 2013. "Crop Production Down in 2012 Due to Drought, USDA Reports." 11 January 2013. Available at: http://www.nass.usda.gov/Newsroom/2013/01_11_2013.asp.

Varshney, R. K., J-M Ribault, E. S. Buckler, R. Tuberosa, J. A. Rafalski and P. Langridge.

2012. "Can Genomics Boost Productivity of Orphan Crops?" *Nature Biotechnology*, 30(12): pp. 1172-1176.

Varshney, R. K., R. Terauchi and S. R. McCouch. 2014. "Harvesting the Promising Fruits of Genomics: Genome Sequencing Technology to Crop Breeding." *PLOS Biology*, 12(6): e1001883.

Victor, P. and T. Jackson. 2015. "Toward an Ecological Macroeconomics" in P. G. Brown and P. Timmerman, *Ecological Economics for the Anthropocene*. New York: Columbia University Press.

Voytas, D. F. and C. Gao. 2014. "Precision Genome Engineering and Agriculture: Opportunities and Regulatory Challenges."*PLOS Biology*, 12(6): e1001877. doi: 10.1371/journal.pbio.1001877.

Wang, L. *et al.* 2014. "Comparative Analyses of C4 and C3 Photosynthesis in Developing Leaves of Maize and Rice." *Nature Biotechnology*, 32: pp. 1158-1165. doi:10.1038/nbt.3019.

Wang, W. *et al.* 2014. "Cassava Genome from a Wild Ancestor to Cultivated Varieties." *Nature Communications*, 5 (5110). doi:10.1038/ncomms6110.

Wang S., S. Zhang, W. Wang, X. Xiong, F. Meng and X. Cui. 2015. "Efficient Targeted Mutagenesis in Potato by the CRISPR/Cas System." *Plant Cell Reports* 34(9): pp. 1473-1476. doi:10. 1007/ s00299-015-1816-7.

Waters, C. N., J. A. Zalasiewicz, M. Williams, M. A. Ellis and A. M. Snelling. 2014. *A Stratigraphical Basis for the Anthropocene*. London: The Geological Society.

Waters, C. N. *et al.* 2016. "The Anthropocene is Functionally and StratigraphicallyDistinct from the Holocene." *Science*, 351: pp. doi:10.1126/science.aad2622.

West, P.C. *et al.* 2010. "Trading Carbon for Food: Global Comparison of Carbon Stocks vs. Crop Yields on Agricultural Land." *Proceedings of the National Academy of Science U.S.A.,* 107 (46): pp. 19645-19648. doi:10.1073/pnas.1011078107.

Westengen, O. T., S. Jeppson and L. Garino. 2013. "Global Ex-Situ Crop Diversity Conservation and the Svalbard Global Seed Vault: Assessing the Current Status." *PLOS ONE*, 8 (5): e64146. doi:10.1371/journal.pone.0064146.

Williams, A. P., R. Seager, J. T. Abatzoglou, B. I. Cook, J. E. Smerdon and E. R. Cook. 2015. "Contribution of Anthropogenic Warming to California Drought During 2012–2014."*Geophysical Research Letters*, August 28, 2015. doi:10.1002/2015GL064924.

Williams, M., J. Zalasiewicz, P. K. Haff, C. Schwägerl, A. D. Barnosky and E. C. Ellis. 2015. "The Anthropocene Biosphere." *The Anthropocene Review*, 2 (3): pp. 196-219. doi: 10.1177/2053019615591020.

Wolt, J. D., K. Wang and B. Yang. 2015. "The Regulatory Status of Genome-edited Crops." *Plant Biotechnology Journal*, Aug. 7, 2015: pp. 1-9. doi:10.1111/pbi.12444.