Revisiting Ester Boserup: the agroecology of agrarian change under population pressure

Marjolein VISSER

ULB, Ecole Interfacultaire des Bio-ingénieurs

marjolein.visser@ulb.ac.be

Membre de GIRAF - Groupe Interdisciplinaire de Recherche en Agroécologie, groupe de contact FNRS

Introduction

Ester Boserup (1910-1999) was a Danish economist and writer. She studied economical and agricultural development, worked at the United Nations as well as other international organizations, and wrote several books. Her most notable book is The Conditions of Agricultural Growth: The Economics of Agrarian Change under Population Pressure (Boserup 1965). This book is seminal because it presents « the real long run view » via a dynamic analysis embracing all types of preindustrial agricultural societies. In doing so, she dismantled the assumption dating back to Malthus's time (and still held in many quarters) that farming methods determine population (via food supply). Instead, she shows that population density determines farming methods.

More about Boserup's analysis

Boserup's book is much more than a simple countering of the views of Malthus. It aims at explaining the characteristics of farming in any specific area and time according to the resource endowment - the land/labour ratio. The more dense population is, the more intensive cultivation becomes. Agrarian economists in the 1950s focused on the Western world, and thus they could appreciate only a relatively narrow range of techniques (just as Malthus reasoned on what he saw happening in early nineteenth century England). Looking at a range of preindustrial rural societies, Boserup could list and describe five farming systems, according to the length of fallow between periods of cultivation of the same piece of land (pp. 15-16):

1- Forest-fallow or slash and burn (at the least 15-20 years of fallow)

2- Bush-fallow (6-10 years of fallow)

3- Short-fallow (1-2 years of fallow)

4- Annual cropping (a few months of fallow)

5- Multi-cropping (no fallow)

The rest of the book explores the consequences of intensification -- i.e. of the move from one stage to the next caused by population growth in a preindustrial context. Each successive stage entails more labour per unit of (total) land and per unit of food produced, and thus the intensification increases the productivity of land but reduces that of labour. A household has to work more to keep the same level of food security or income. Finally, the intensification process also brings about institutional change, and this was another innovative aspect of Boserup's model. When Boserup was writing, the first agricultural revolution of Modern Times (the substitution of fodder crops and leys for annual fallow in temperate Europe) was considered an epochal change with far-reaching implications for the entirety of world history. This view is still diffused, if no longer dominant. In Boserup's model however, that revolution was only part of the long-run process of world-wide intensification.

Phase 6 and the contours of Phase 7 sensu Boserup

Ester Boserup gave no indications about the time it takes to evolve from one stage to another. Even if the original evidence comes from a transverse analysis of a range of societies in the 1940s, the leap from changes in space to changes in time (diachronic studies) is huge, because the agrarian changes described by Boserup do not happen in a couple of decades, but rather centuries. Furthermore, Boserup excluded from her analysis the advent of a third production factor: (financial and industrial) capital (Turner and Fischer-Kowalski 2010). The twentieth century saw substitution of agricultural labour and land for financial capital (invested in infrastructure, machinery and petrochemicals). This second agricultural revolution of the Modern Times, or Phase 6 sensu Boserup, has offered some (temporary) release from population pressure, but also brought a host of new problems. And finally, Boserup did not discuss the fact that agricultural intensification does not happen without a serious degree of ecological crisis, that this crisis can actually last for decades or centuries, (Kjærgaard 1995; Mazoyer and Roudart 1997), and that many societies all over the world have actually experienced collapse instead of intensification because of an overstretched resource base (Diamond 2006). We are only beginning to appreciate that the substitution of labour and land for financial and industrial capital is not the final nor the only solution to the uneasy food/people/environment equation. So what are the contours of Phase 7?

The aim of this paper is thus:

1- to put into perspective Boserup's analysis of preindustrial societies with the help of more recent books (Diamond 1997, 2006; Kjærgaard 1995; Mazoyer and Roudart 1997; Pimentel and Pimentel 1979, 2008; Slicher Van Bath 1963; Tainter 1988);

2- to redefine the concepts of yield, intensification and productivity growth from an agroecological perspective;

3- to simplify the complexity of this matter by presenting a unifying conceptual framework for a transition towards post-industrial food systems based on natural capital.

Methods and Results: linking concepts from different fields

The efficiency of food production factors: what is intensification?

The idea is firstly to redefine (food production) efficiency taking into account historical and energetic considerations, with Boserup's book as a starting point. It should be stated from the outset that when talking about a production process, the concepts of efficiency (which differs from efficacy!), productivity, yield or rate of return always refer to some output/input ratio. But there are many output/input ratios related to food production. The exact terms of that ratio need to be defined, measured and used as a yardstick of "progress". So when using one of these words, both the types of input and output and the units of measurement need to be specified. The same applies to intensification. Intensification happens when there is a well-defined increase of input x with the hope to obtain a more than proportionate and well-defined response of output y so that an equally well-defined output y /input z ratio improves. This implies that when talking about intensification, one should be specific about the kind and unit of measurement of that intensification.

Boserup's analysis was based on classical agricultural economics. Classical economic theory considers labour and capital as the basic production factors. Not so in agricultural economics, where land is the first and foremost production factor, followed by labour in pre-industrial contexts. Boserup described agrarian change under population pressure as a forced intensification process, which she defined as the replacement of land by labour to raise the productivity on that land. In other words to increase the yield (productivity of the land, food produced per ha), more work per ha is needed. Of course this does not happen spontaneously, which is why she stated that "necessity is the mother of invention". Intensification happens under population pressure but only when all available land is brought into cultivation.

With these production factors in mind as denominators, two broad definitions of efficiency are classics in agricultural economics: (useful) output per unit of land (the conventional yield) and output per labour unit or per manhour. Pre-industrial intensification was about raising the productivity of the land by inputting more labour, at the expense of labour efficiency. The industrialisation of agriculture (we call this Phase 6 following Boserup's last preindustrial phase 5) is when capital was added as the third production factor in agriculture. Industrial intensification is about raising mainly labour efficiency (and to a lesser degree productivity of the land) by huge inputs of industrial capital, at the expense of "capital efficiency". I quote "capital efficiency", because in agriculture, classic economic theory does not seem to handle "capital efficiency".

In a monetary economy, economists prefer to get rid of the variety of biophysical measurement units by converting all inputs and outputs to monetary units and calculate an overall cost-efficiency. However, this implies putting a price on each and every biophysical unit of land, labour and capital. The price of whatever we want to price depends on its **perceived scarcity**. There are at least three problems with this conversion depending on price.

First, there is a bias toward short-term and small-scale measurements, since prices of the future are subject to a great deal of uncertainty. Long-term efficiency is thus neglected in favour of short-term efficiency, and directly useful output is favoured over indirectly useful output. Boserup already pointed to the fact that subsistence and market-oriented agriculture obey to different production logics with regard to output/input ratios.

Second, agricultural prices fluctuate and market reactions to these fluctuations tend to exaggerate the spikes and valleys. Big fluctuations put farmers out of business.

Third, when intensifying with external inputs (that need to be paid for), the intensification logic will depend on the relative prices of outputs compared to inputs and the search for a "financial intensification optimum" follows a different logic than the search for a "biophysical intensification optimum". When the prices of industrial energy are low, industrial intensification has an edge over other intensification logics, or the other way round, as some subsistence farming contexts show.

Let's now remind the laws governing intensification with regard to different production factors (1), bring in energy considerations (2) and finish with ecological insights on food production (3) to draw the contours of Phase 7 sensu Boserup.

The law of diminishing returns and trade-offs: the importance of context

The concept of productivity or efficiency is relative. This historical analysis should make clear that "Improving the efficiency of production" without further specification is a meaningless statement, since there are trade-offs between efficiencies with regard to different production factors and we never use only one production factor.

Trade-offs arise because intensification in general obeys the universal law of diminishing returns: the marginal return (= output response) of each extra dose of whatever input diminishes as the total input increases. This law can be applied in different ways.

First, per type of output/input ratio, the graphical illustration of the law already shows that every next "input dose" yields a lower marginal return compared to the previous input dose.

Second, one type of input does not add to another type of input but partly replaces it. Hence the trade-offs.

Third, while aiming for one type of output (typically today: short term, financial, directly measurable) we lose out on other types of outputs (longer term, biophysical, indirect). So there are also trade-offs between different outputs (measured and unmeasured)[1].

Finally, development pathways seemingly favour increasing complexity as an answer to efficiency or productivity problems along the way. Tainter (Tainter 1988) viewed societal complexity as an input factor with increasingly smaller returns on efficiency and finally negative returns, bringing forth the eventual collapse of overly complex societies.

Energetics of agroecosystems (Figure 1): the neglected importance of living energies

If money is the master resource of economists (in a monetary economy), energy (expressed in Joules) is the master resource of ecologists. Energy is the ultimate driver of any (agro-)ecosystem, whatever the price we are willing to pay for it now, whatever its perceived scarcity. Ecologists reason with energy fluxes through (agro)ecosystems. Life on earth starts with solar energy being fixed through photosynthesis by autotrophs as plant biomass. On a planetary basis, the average solar yield is very low, typically around 0.1 % (Smil 2008).

This chemical energy is dissipated again as heat. This happens preferably in a slow-release modus, through respiration by living organisms, but also sometimes in a fast-release modus, through incineration (e.g. in slash and burn agriculture or the burning of crop residues, forest or savannah fires). The earth thus acts as an intermediate compartment for the storage and release of a tiny part of the solar energy it receives continuously. Once fixed through photosynthesis, this energy flushes slowly through an endless series of heterotrophs in the food system. Typically, these heterotrophs absorb and respire only a small part of what they ingest, the bigger part leaves the organism before absorption. And crucially, the energy discarded by one compartment in a food web becomes food energy for another compartment. However, the minerals contained in this food energy are recycled. Depending on its chemical characteristics, each mineral has a typical cycle. But this cycling cannot be efficient without the accompanying food webs that basically flush solar energy through the system.

Our premise is that, rather than yield or labour efficiency, energy efficiency (or productivity) matters most, yet it has never got the attention it deserves. Measuring efficiency in terms of useful food energy output (to be converted in Joules) obtained by inputting various types of other energies seems ecologically meaningful. Inputs in terms of labour and capital should therefore be converted into energy units. This has indeed been done in various ways and for a variety of crops and systems since the seventies of last century. It is important to understand that this ratio is unitless and that the threshold is one (1). If we want efficient food systems, the energy efficiency (from production to consumption) should be at the very least higher than 1: we should reap more energy as food (output) than we invest (input). Ever since David and Marcia Pimentel first calculated energy efficiencies of food production in the seventies and up to the latest edition of their book (Pimentel and Pimentel 1979, 2008), we know our food energy efficiencies have plummeted far below the threshold of 1 during the twentieth century. However, food energy efficiencies of so called primitive farming systems, with far less or no

---

[1] There are many concrete and lively illustrations of these broad « laws » governing productivity and intensification but it would bring me too far to develop these here.

fossil energy inputs, exhibit energy efficiencies far above 1.

If we accept that agricultural intensification is about raising the useful output of each hectare of cropland by inputting extra energy, coming from « elsewhere », it is useful to construct a typology of "elsewhere" energies (Figure 1). When considering energy fluxes through food systems, Gliessman (Gliessman 2006) distinguishes ecological energy (derived from the sun and intercepted through photosynthesis) from cultural energy (spent by humans to optimise biomass production and transfers). There are various types of cultural energy, which can be classified in two simple categories: biological (renewable) and industrial (non-renewable) cultural energy.

Another way of looking at these three basic categories (ecological, biological and industrial) is by making the distinction between living and non-living energies. There are thus two types of living energies: solar energy that is fixed but not directly used as (human) food, and solar energy that is redirected culturally as an additional input to food systems. These are the renewables, to be contrasted with non-living energies, which are non-renewable[2]. Stated differently: if non-renewables get scarce and prices go up, capital will become scarce, expensive, more difficult to accumulate, maintain, employ. There is thus no other option but to turn to renewable or living energies. However, this does not mean we have to turn back the clock to the human toil we experienced at the eve of the Industrial Revolution. What this means down to earth is developed next.

(H)ASS concept and fertility transfers from source to sink: space-time substitution (Figure 2)

HASS means (Hortus-)Ager-Saltus-Silva and Mazoyer and Roudart (1997) introduce these concepts when describing the post-forest farming systems that have developed in Europe once Phase 1 sensu Boserup was not an option any longer due to population pressure (from Antiquity onward). Every agroecosystem can be thought of as a specific HASS space-time continuum with a specific structuring and functioning of the different elements. But broadly speaking, HA function as fertility **sinks** whereas SS function as fertility **sources**. Figure 2 is a conceptual diagram showing the connectivity of these landscape components.

The genius of Boserup was to understand that, in preindustrial societies, agrarian change under population pressure forced farmers to substitute inputs: from ecological energy (built up during long fallow phases, 1-3) to biological cultural energy (human toil) with short or zero fallow phases (Phases 3-5). If we prolonge boserupian thought, Phase 6 is when biological cultural energy is replaced by industrial cultural energy.

To get an idea of the contours of Phase 7 sensu Boserup on the production side of food systems (and it all starts there), it is important to acknowledge that the central problem of all (farming) times has been how to replenish the fertility of the land on which we grow our staple crops. This land is called the **ager** (from Latin: a place that is tilled) and the **ager** is a fertility sink (Figure 2). Soil fertility is defined here as the total of living and dead biomass of an agroecosystem (compartment), partially or potentially transformed to soil organic matter. Since this transformation involves respiration, hence energy dissipation, fertility equates biochemical energy (carbon bounds with minerals in it). And since carbon bounds mean biomass, fertility can be generated and accumulated spontaneously (without expenditure of additional cultural energy) through the accumulation of biomass on a piece of land, typically during ecological succession. This refers to Gliessman's ecological energy. If this spontaneous process is not allowed to happen (typically under population pressure), this ecological energy can also be transferred from one place to another (however with expenditure of additional cultural energy,

---

[2] An exception with which we choose not to reason for the moment is nuclear energy. For the moment indeed, apart from electricity derived from nuclear reactors, industrial inputs of food production systems are non-nuclear.

first biological, recently industrial). This transfer happens from sources other than the **ager** toward the **ager**. These other sources are the **saltus** and the **silva** (See Box 1). Sources of fertility are thus intimately linked to perennial vegetation because perennials produce enduring fertility (ecological energy) through the storage of sunlight in complex carbon polymers. Saltus is dominated by herbaceous plants, mostly grasses (lots of cellulose, no lignin) and **silva** is dominated by woody plants (a bit of cellulose, but above all lots of lignin).

Now, it is important to acknowledge that ager, **saltus** and **silva** are linked both in time and in space.

Through ecological succession (linkage in time), an **ager** evolves to **saltus** over a couple of years and to **silva** over a couple of decades. Meanwhile fertility is replenished *spontaneously*. The focus of any farming system is on the **ager**, where the main concern is to restore fertility in between cultivation cycles and prevent weed invasion. The ager is thus a sink of fertility, albeit an intermediary one, because the final sink is the place of intermediate and final food consumption (human dwellings and animal housing), with the development of the **hortus** to take stock of all this concentrated fertility. Historically, the **hortus** is also the habitat of the small-sized omnivorous animals (pigs and poultry) that feed on household leftovers, in a further effort to intensify food production preindustrially. Farming systems in Phases 1-3 of Boserup explicitly use ecological succession and the concomitant soil fertility restoration mechanisms to regenerate fertility of the **ager** with very little (but growing) work input. The **ager** thus shifts and farmers still use a shifting cultivation system. In Phases 4 and 5 however, the **ager** becomes permanent and from then on, a linkage in space between **ager**, **saltus** and **silva** becomes necessary. In order to restore the fertility of a permanent **ager,** mechanisms of horizontal fertility transfer from sources to sink(s) are put in place, mainly through grazing and dung transport. Refining of this technique was the essence of successive farming revolutions in temperate Europe (Mazoyer and Roudart 1997; Slicher Van Bath 1963). But these transfers involved ever more work to be done. In other words, throughout Phases 2-5, ever more biological cultural energy had to be added to replace the ecological energy foregone through the shortening of the fallow.

In Europe and by extension the temperate regions of the earth, the essence of the First Agricultural Revolution of Modern Times was to target specific early-succession plant species, grow seed of these and establish leys (or temporary meadows, a "domesticated" type of **saltus** based on legume-grass coupling) that can quickly build up fertility in the upper soil layer. The weedy first phase of ecological succession was thus "short-circuited", and the productivity of these leys was enhanced through ruminant livestock that could make valuable dung out of this biomass.

In tropical regions however, many obstacles exist to horizontal fertility transfer mechanisms, with or without through grazing and dunging. Tropical **saltus** is rarely nutritious for the main ruminant herbivores and some tropical animal diseases hinder livestock enterprises. Also, tropical soils are much more vulnerable than temperate soils once exposed to intense sunshine and heavy rainfall[3]. And third, the heat makes human physical effort very difficult to sustain for more than a couple of hours. On the other hand, agroforestry makes explicit use of **silva** to restore/enhance/maintain the fertility of the **ager**. Agroforestry systems have evolved both in tropical as well as in temperate regions along with grazing systems, to make use of the fertility replenishment potential of trees in the landscape.

We can conclude from this review that the refinement of both techniques (reintegrating selected **saltus** and **silva** elements into the ager) had already gone some way in preindustrial times (Kjærgaard 1995; Mazoyer and Roudart 1997; Slicher Van Bath 1963) but further research

---

[3] Space does not allow to expand on this but a impressive amount of literature exists on the problems replenishing fertility of tropical soils otherwise than through long fallow phases.

and development was undercut, locked out, crushed or simply displaced by an industrial logic during the twentieth century.

Discussion (Figures 3 and 4)

We now need to draw together the elements explained above that come from different fields, disciplines and insights. If we reinterpret Boserup's typology of farming systems under population pressure within the HASS-framework, the following pattern emerges:

- Moving out of the forest fallow towards shorter fallows has historically meant that we have forgone the ecological energy generated by woody vegetation through spontaneous ecological succession. We have thus dissociated ever more **ager** (sink) from **silva**, our first possible source of fertility.

- The only way this dissociation remained viable in preindustrial times was by turning to the other source of fertility (**saltus**) and by inventing ever more refined systems of horizontal fertility transfer from **saltus** to **ager** with the development of livestock enterprises. At least, that's how it went in temperate preindustrial Europe up to the eve of the Industrial Revolution.

- The preindustrial development pathway of farming systems under population pressure has thus been from small patches of **ager** within a **silva** matrix toward a mixture of silva remnants (hedges and single tree rows) within a matrix of **saltus** and **ager** (Figure 3). Industrialisation (Phase 6) has meant a further isolation of the **ager** from its potential fertility sources. Huge expanses of **ager** are now being cropped without any connectivity with perennial vegetation in the landscape, thanks to the availability of cheap industrial energy. But this is energetically inefficient and underutilises or even wastes the other types of energies. Moreover, inappropriate management has degraded extensive swaths of land especially in arid and tropical environments and the investments in cultural energy (whatever type, biological or industrial) needed to restore these are tremendous (Roose et al. 2011).

- A the eve of the Industrial Revolution, farmers literally worked over 12 hours a day sunlight permitting and many more days a year then ever before (Kjærgaard 1995). The human toil of work on the farm had become unbearable. At least in the beginning of the industrialisation of farming (the steepest part of the curve of diminishing returns), the substitution of labour for capital was a blessing rather than a curse. However, we've clearly moved beyond the hilltop of the curve of diminishing returns – at least in biophysical terms. In addition, once industrial energy becomes scarce again, there is not other option for our food systems but to make better use of the living energies that have been neglected through trade-off mechanisms of the twentieth century. These living energies are the **saltus** and **silva** components on one hand (ecological energy), and biological cultural energies on the other. Thus are the contours of Phase 7 sensu Boserup. We need to move back to the middle of the triangle of Figure 4.

- Apart from "simply" addressing population growth itself, one burning question remains unanswered: can societies where some type of fallow farming still dominates (most countries in subsaharian Africa for example) gracefully leapfrog Boserup's stages: (1) accepting a higher workload even though the returns on investment do not come immediately and (2) without gliding off into Malthusian scenarios of irreversible resource degradation (Jouve 2004)?

Conclusion

In shaping our food systems, the type of efficiency we privilege is a matter of context and **perceived** scarcity. In the past, we have accepted increasingly poor energy efficiencies in our collective obsession with increasing yield (output of each ha of cropped land) and labour efficiency (output of each hour spent) and blindness for inconvenient trade-offs such as increasing capital efficiency. If we accept that energy efficiency matters most in the long run, then we should adapt our food, farming, energy family planning policies so as to raise the energy efficiency of our food systems globally.

At the eve of the industrial revolution (end of the 18th, early 19th century), one factor limiting further intensification of our food system without the aid of industrial energy was knowledge about its inner workings. There was no such thing as ecology. Malthus did not know about agrarian change under population pressure. Liebig and Mitscherlich still had to fine tune the law of decreasing returns on mineral fertiliser inputs (and proved to be wrong). Compost was not invented yet. Nobody had measured and experimented with the edge effect on yield when mixing species on the **ager**.

By contrast, industrialisation was on its way, and the discovery of seemingly endless oil deposits paved the way for the industrialisation and capitalisation of our food systems. As oil was perceived endlessly available, its pricing was low compared to labour and land – up to today. As a result, we seem to be able to produce cheap food at an absurdly low energy efficiency. Today, we know these seemingly endless oil deposits will end soon. In addition, the way we have chosen to inject non-living energies in our food system was not by looking for synergies with the other options, on the contrary. Industrial logics applied to food systems crush or obscure the potential of the living energies at our disposal. It is thus pointless to continue along this path. Energy will become scarce again, limited to living energies. But the big difference with two centuries ago is that we now have scientific knowledge and a huge but untapped research potential to redesign food systems in a post-industrial but newly capitalistic way, in a new question for energy efficiency. This redesign should fully acknowledge the following facts:

1- It is key to make the most of our natural capital first, without further destroying precious natural heritage firstly but secondly also to limit the amount of human toil. Perennial vegetation (**saltus** and **silva**) is crucial, firstly to replenishing the fertility of the **ager** and secondly, to the ecological management of weeds, pests and diseases. Reintegrating **saltus**- and **silva**-components into the **ager** is the universal recipe to address the main problems of any farming system worldwide, but this universal recipe has to be adapted to local contexts (climate, soil, history) worldwide. This means that in some contexts, it is easier to redesign food systems working with **saltus** whereas in other contexts, it is easier (more energy-efficient) to work with **silva**. In still other contexts, a combined approach is potentially the most productive way. But they need to be designed and refined, and for this to work we need our biological cultural energies, our social and human capital, our capacity to learn and make others learn.

To make the most of our natural capital without further destruction and to adapt a universal recipe to local contexts, the (re)development of the right human and social capital (living energies) is crucial – paying due attention to social justice and dignity, lowering complexity, increasing localness. During the twentieth century, we have truly destroyed farmer's livelihoods worldwide. As a consequence, we are losing them, and with them badly needed human and social capital for when the sources of industrial capital will run dry. Restoring this badly needed human and social capital in great number requires radically different models of research and development.

References

Boserup, E., 1965. The Conditions of Agricultural Growth: The Economics of Agrarian Change Under Population Pressure Earthscan, Oxford.

Diamond, J., 1997. Guns, germs and steel. The fate of human societies, Norton & Company, New York.

Diamond, J., 2006. Collapse. How societies choose to fail or to survive, Penguin, USA.

Gliessman, S. R., 2006. The ecology of sustainable food systems, CRC Press, USA.

Jouve, P., 2004. La croissance démographique, frein ou opportunité pour une intensification agricole durable en Afrique subsaharienne? Courrier de l'Environnement de l'INRA. 52, 101-106.

Kjærgaard, T., 1995. The Danish Revolution, 1500–1800. An Ecohistorical Interpretation, Cambridge University Press, Cambridge.

Mazoyer, M. and Roudart, L., 1997. Histoire des agricultures du monde. Du néolithique à la crise contemporaine, Seuil, Paris.

Pimentel, D. and Pimentel, M., 1979. Food, energy and society, Hodder Arnold, USA.

Pimentel, D. and Pimentel, M., 2008. Food, energy and society, Taylor & Francis Group, Boca Raton.

Roose, E., Bellefontaine, R. and Visser, M., 2011. Six rules for the rapid restoration of degraded lands: synthesis of 17 case studies in tropical and Mediterranean climates. Sécheresse. 22, 86-96.

Slicher Van Bath, B. H., 1963. The agrarian history of western Europe, Edward Arnold, London.

Smil, V., 2008. Energy in Nature and Society: General Energetics of Complex Systems, MIT press, Cambridge, Massachusetts.

Tainter, J. A., 1988. The collapse of complex societies, Cambridge University Press, Cambridge.

Turner, B. L. and Fischer-Kowalski, M., 2010. Ester Boserup: an interdisciplinary visionary relevant for sustainability. Proceedings of the National Academy of Sciences. 107, 21963-21965.