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Grantham Centre for Sustainable Futures

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A sustainable model for intensive agriculture

It is widely accepted that global food production will have to increase dramatically over the coming decades to meet the needs of growing populations and developing economies, and that this will be increasingly difficult as we feel the effects of climate change. Intensive agriculture is currently unsustainable so a different path is needed. Sustainable intensification is heralded as the saviour of agriculture but what does it mean in practice? This paper sets out a model that combines the lessons of history with the benefits of modern biotechnology, to redesign sustainability in intensive agriculture.

Sustainable intensification is heralded as the saviour of agriculture, but what does it mean? At first glance, the terms "sustainable" and "intensification" appear to be incompatible: indeed as the FAO has noted[1], whilst agriculture based on the intensive use of inputs has increased global food production over the last half-century, it has in the process, depleted the natural resources of many agro-ecosystems, jeopardising future productivity. The new paradigm of sustainable intensification of agriculture[1,2] attempts to balance these competing imperatives, envisaging a system in which yields are increased from the same area of land while conserving resources and reducing negative impacts on the environment. But the concept of sustainable intensification has proved controversial[3] with widely different views of what it could or should look like on the ground.

Achieving sustainability targets within agricultural systems requires us to evaluate whether the agricultural technologies currently at our disposal are capable of delivering the necessary efficiency savings.

Intensive agriculture is currently unsustainable.
Under the intensive farming system, current crop yields are maintained through heavy fertiliser applications, which are unsustainable, because they:

1. require high energy inputs to supply inorganic nitrogen via the industrial Haber-Bosch process, which consumes 5% of the world's natural gas production and 2% of the world's annual energy supply;
2. depend on the mining of non-renewable rock phosphorus (P), diminishing stocks of which will become increasingly difficult to extract in the coming decades as the easiest to access, high P content ore has already been mined; and
3. allow nutrients to wash out and pollute fresh and coastal waters, causing algal blooms and lethal oxygen depletion, as well as dispersing nutrients in the ocean. Despite these high environmental costs of conventional intensive agriculture, and the widespread application of crop breeding programmes, we are unable to improve the yields of several major crops, which have stagnated in the past 15 years (Fig. 1).

Elite modern crops are optimised for a system of high-nutrient artificial inputs and chemical control of pests and diseases; they have consequently lost their natural reliance on microbes to extract complex nutrients from the soil and for defence against natural enemies. Soil is becoming a hydroponic system: a physical substrate to support plants, but providing little else. In particular, deep ploughing has caused a decline of soil organic carbon, reducing soil's abilities to retain water and supply nutrients, and a loss of structure that allows rapid soil erosion. As soil is lost rapidly but replaced over millennia (Box 1), this represents one of the greatest global threats for agriculture. It is the degraded state of our agricultural soils that appear responsible, at least in part, for the yield plateau (Fig. 1).

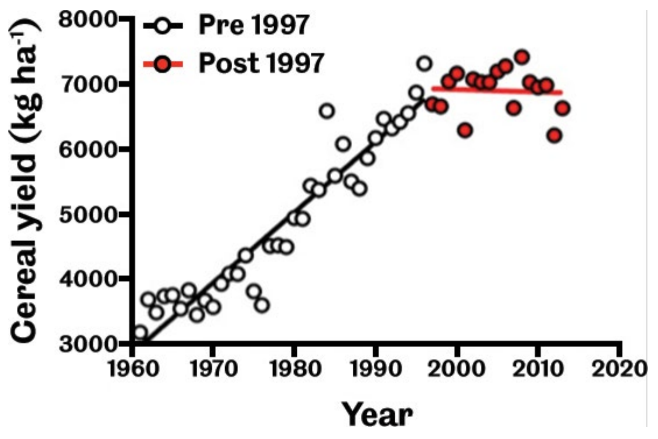

Figure 1: Yield stagnation in cereals. Graph illustrating the yield trajectory for several major cereal crops in the UK. Data from the World Bank.

Sustainability needs good soil management.

"The nation that destroys its soil destroys itself."
Franklin D. Roosevelt (1937)

Nineteenth century farmers had little access to artificial fertilizers, and consequently had to manage the soil well. Soil management combined the application of manures and the rotation of annual crops with grass and nitrogen-fixing legume cover crops (leys), which recharged soil carbon and nutrients as well as rebuilding soil physical structure. These conservation agriculture methods are today practiced in organic agriculture, where the resultant benefits of increased organic matter for soil structure, water-holding abilities, and nutrient availability are well established. However, organic systems do not utilise advances made in agrichemistry inputs, *meaning that yields are limited*, and rendering organic agriculture unsustainable in terms of feeding a growing global population.

Box 1: Soil loss, an unfolding global disaster

- Nearly 33% of the world's arable land has been lost to erosion or pollution in the last 40 years.
- Erosion rates from ploughed fields averages 10-100 times greater than rates of soil formation.
- Erosion leads to preferential removal of organic matter and clay, removing nutrients and releasing CO_2.
- It takes about 500 years to form 2.5cm of topsoil under normal agricultural conditions.

Historically, good soil management was supplemented by the collection and application of "night soil" (human excrement), a practice that continued into the twentieth century. In a historical example of the circular economy, this closed the nutrient loop, recycling organic nitrogen

[1] FAO (2011). Save and grow: A policymaker's guide to the sustainable intensification of smallholder crop production, Rome

[2] The Royal Society (2009). Reaping the Benefits: Science and the sustainable intensification of agriculture, London

[3] Garnett T and Godfray C (2012). Sustainable intensification in agriculture. Navigating a course through competing food system priorities, Food Climate Research Network and the Oxford Martin Programme on the Future of Food, University of Oxford, UK

and phosphorus back into soil. Additional benefits for soil organic matter are achieved in modern agriculture from the "no-till" method, where direct drilling is used to sow seeds, and cover crops and weeds are removed using herbicides, and ploughing is not needed. This approach reduces the oxidation of soil organic matter, conserving soil structure. While the enhanced use of cover crops and leys almost certainly requires an increase in the land area used in agriculture, there is potential for less land to be in *active cultivation* at any one point in time. This then leads to an extensified agriculture system with simultaneous intensification of crop production (Fig. 2).

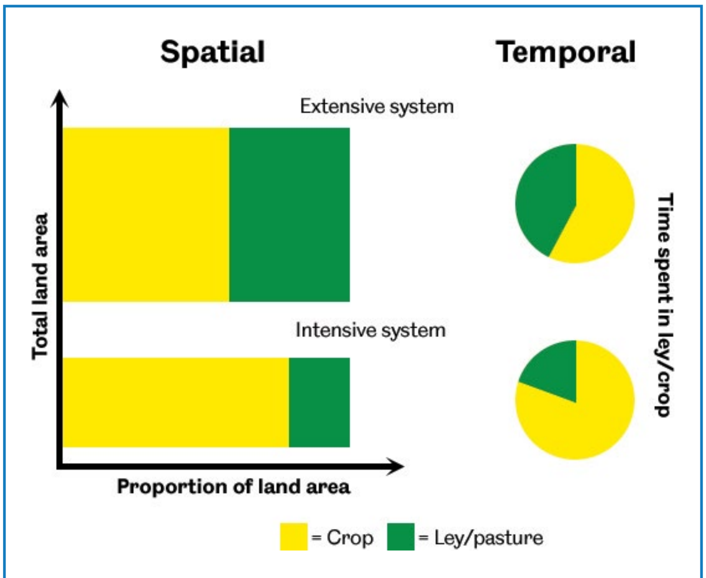

Figure 2: Representation of an extensified agricultural system in northern temperate regions. Current pasture leys used for dairy and meat production are turned over to arable crops as part of a long-term rotational system. This increases the relative time any given field spends in ley, and so restores desirable soil properties limiting required inputs.

A sustainable model for intensive agriculture could combine the lessons of history with the benefits of modern biotechnology, and is founded on three principles:

1. Managing soil by direct manure application, rotating annual and cover crops, and practicing no-till agriculture. These practices allied to "conservation agriculture" restore soil organic matter, structure, water-holding capacity and nutrients, averting soil loss (Box 1) whilst benefiting crops.
2. Using biotechnology to wean crops off the artificial world we have created for them, enabling plants to initiate and sustain symbioses with soil microbes. These symbioses allow crops to exploit microbial biology to tap into soil organic nutrient reserves, and prime plants to better defend themselves against pests and diseases (Fig. 3).
3. Recycling nutrients from sewage in a modern example of the circular economy. Inorganic fertilisers could be manufactured from human sewage in biorefineries operating at industrial or local scales. A number of technical challenges impede the immediate adoption of this idea, but these can readily be addressed through research.

Enhancing the biological functionality of soils allows them to store more water and nutrients, and support microbial communities that can boost plant health through direct suppression of soil-borne diseases and priming plant immune systems. A sustainable soil-centric reengineering of the agricultural system would reduce the need for fertiliser inputs and pesticide application, and require less irrigation, thus contributing towards safeguarding finite natural resources.

In order to facilitate such a wholesale redesign of the agricultural system, we need to assess the potential scientific, economic, cultural and political impediments to this happening, and resolve the potential benefits of this redesign for sustainability. In doing so, we could reduce our dependence on energy-intensive and non-renewable inorganic fertiliser, reduce fertiliser pollution of watercourses, and create a soil fit for future generations. Of course, no one model equally fits all problems, different agricultural scenarios (geography, climate, crop) might benefit from our approach more than others and any redesign of the agricultural system needs to be sufficiently flexible to accommodate this.

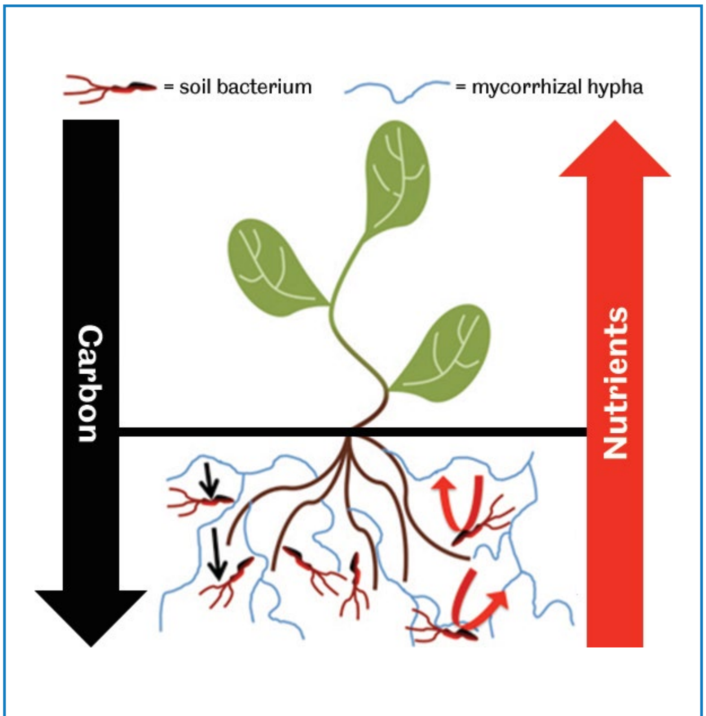

Figure 3: A symbiosis between plant and soil microbes (bacterial and mycorrhizal fungal) involves a two-way exchange, rather like a financial transaction. The plant pays with carbon to obtain nutrients from the mycorrhizal fungus, which in turn can stimulate microbial communities that mobilise recalcitrant nutrients such as phosphorus, suppress soil-borne diseases and prime plant resistance against pests and diseases. Some of these benefits are analogous to those we enjoy from microbes in our gut. Because soil microbes can access nutrients in organic matter which plant roots cannot, this gives plants access to otherwise unavailable soil nutrient sources. Organic matter is replenished using conservation agriculture practices.

About the Grantham Centre for Sustainable Futures

The Grantham Centre for Sustainable Futures is an ambitious and innovative collaboration between the University of Sheffield and the Grantham Foundation for the Protection of the Environment. Our sustainability research creates knowledge and connects it to policy debates on how to build a fairer world and save natural resources for future generations.
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About P^3

Plant Production and Protection (P^3) is a centre of excellence for translational plant and soil science encompassing the breadth of plant and soil science expertise within the University of Sheffield. P^3 capitalises on our unparalleled ability to work across biological scales, from genome to the global atmosphere, and translates our intellectual capital into solutions to real-world problems in collaboration with our industrial, NGO and third sector partners.
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P^3 Plant Production and Protection

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Duncan Cameron is Professor of Plant and Soil Biology and a Royal Society University Research Fellow in the Department of Animal and Plant Sciences at the University of Sheffield. He is also co-Director of the P^3 centre of excellence for translational plant and soil science. His work has included industry collaborations that have helped develop sustainable agricultural practices and found innovative new ways feed the growing global population. He is a recipient of the World Economic Forum's Young Scientist Award for his work in translating fundamental advances in plant science into practical agricultural solutions.

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Colin Osborne is Professor of Plant Biology in the Department of Animal and Plant Sciences at the University of Sheffield. His research experience spans two decades and he currently heads up a lab group looking at the controls on plant productivity. In the Grantham Centre, Colin oversees the training and development of the Grantham Scholars, equipping them with the tools to become sustainability experts and policy advocates.

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Mark joined the University of Sheffield in 2015 on secondment from the Department of Business Innovation & Skills, where he was leading on research, education and skills links with India. Immediately prior to that, he held a series of international positions with the UK Government's Foreign & Commonwealth Office Science & Innovation Network where he was responsible for developing bilateral relationships and collaborations in science and innovation.

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