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comment

Growing innovations for the bioeconomy

Agriculture is often viewed as a source of problems needing innovative solutions. But agriculture can actually be a source of innovations for the bioeconomy, if researchers embrace the cultural changes needed.

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Many nations have now published strategies outlining their plans for the bioeconomy[1–3] — the section of the economy fuelled by scientific and technological innovations in the biosciences. The bioeconomy promises to be a renewed source of economic growth and job creation, with over 22 million people already employed in the sector (worth more than €2 trillion annually) in the European Union, and over 4 million in the US.

Alongside its economic promise, the bioeconomy is anticipated to contribute significantly to the implementation of the UN Sustainable Development Goals (www.un.org/sustainabledevelopment/sustainable-development-goals) through its impact on health, food security, sustainable energy and the conservation of scarce natural resources. It is the integration of science with business and society, and the triple promise of increasing innovation, growing economies and solving sustainable development challenges, that give the bioeconomy so much power as a policy concept.

The bioeconomy aspirations of governments and industries have arisen from the recognition of the enormous potential of recent technological advances in the biosciences — particularly high-throughput genome sequencing and 'omic' technologies (such as transcriptomics, proteomics and metabolomics), high-throughput phenotyping (Fig. 1), computational biology and synthetic biology[4]. These technologies enable the generation of huge datasets and the integration of knowledge across all levels of biological organization, from genes to individuals to communities. They have profoundly altered the way causal gene discovery, functional analysis, whole-organism design, crop and animal improvement and whole-systems analysis can be approached and achieved. As such, these technologies are anticipated to drive truly transformational changes in human health, agriculture and resource management, and in the manufacture of cleaner and greener energy and industrial products from renewable and more sustainable sources. The ability to sequence and compare genomes of patients cheaply and quickly, for example, is anticipated to lead to more personalized healthcare. Biotechnology and genome editing are anticipated to significantly accelerate the breeding of more resilient crops and the development of smart crop protection systems.

The agri-economy

Agriculture remains the essential cornerstone of food provision for the world's growing population. Unfortunately, however, agriculture is often considered to be a source of problems that require innovative solutions, rather than being seen as a source of innovations. Publically funded agricultural research is often viewed as solid and traditional, rather than progressive and game-changing. The decline in the number of researchers in agricultural disciplines such as agronomy, weed science, crop physiology and breeding, and the loss of publically funded breeding programmes in many countries, are symptomatic of these views. At the same time, most private investments in the bioeconomy have not been directed at agriculture, but at the pharmaceutical and biomedicine industries, followed by the green chemistry, biomaterials and industrial biotechnology industries.

Agriculture is undergoing a transformation due to the use of Global Positioning Systems in concert with remote sensors and intelligent systems. For instance, on-board tractor performance monitoring systems now enable farmers to optimize input operations to enhance field productivity[5]. These innovations, however, are not being driven by researchers in the agricultural sciences, but rather by experts in information management technologies, electronics and engineering.

In Europe, a major path to the bioeconomy has been the establishment of 'bioeconomy clusters' — regional aggregations of small- and medium-sized enterprises, research centres, universities and (occasionally) investors working towards shared goals. This development was spurred by Germany's first bioeconomy cluster in Halle, Saxony-Anhalt (http://en.bioeconomy.de). Here, timber, chemical, plastic material and plant engineering industries and research organizations work together on the use of non-food biomass for energy and new materials production. Facilities such as biorefineries are often at the centre of such clusters, such as the Fraunhofer Centre for Chemical-Biotechnological Processes in Leuna, which uses cutting-edge chemical and biotechnological technologies for the extraction of chemical products from biomass for diverse industrial uses. Similar aggregations have been established throughout the world, and include biomedical centres that bring together all manner of businesses, from pharmaceutical companies to device manufacturers.

No equivalent bioeconomy clusters have so far been developed specifically in the agricultural sector, although some, such as the UK BioVale cluster (www.biovale.org) of Yorkshire and the Humber (also concentrated around a biorefinery), carry out some research into the utilization of food waste. Government initiatives aimed at connecting and coordinating agricultural research activities with industries (such as AgriTech centres in the UK) are also a step in the right direction. For instance, the

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Figure 1 | A Field Scanalyzer, recently installed at Rothamsted Research in the UK. The device supports a motorized measuring platform with multiple sensors. It is fully automated and can operate continuously. On-board illumination facilitates the data collection. Sensors include multi-wavelength imaging systems, a sensor to measure chlorophyll fluorescence decay kinetics, and a laser system for 3D visualization and crop height determination. Technologies such as this provide field phenotype data of unprecedented detail and accuracy that can inform new crop improvement strategies, and thereby help fuel the bioeconomy.

newly established UK AgriMetrics centre (www.agrimetrics.co.uk) serves as a portal to all publically available data relevant to the food system. This agricultural informatics platform combines all the necessary software tools for the integration of large datasets from crop and animal breeding, agronomy and farming systems, according to the needs of users throughout the food sector.

Complexity, conflict and constraint

Sustainable agriculture and the provision of sufficient, healthy and safe food rank highly among the objectives of most national bioeconomy strategies. Despite this, the agricultural sector has been slower in realising opportunities in the bioeconomy. There are arguably four main reasons why the agricultural sciences are lagging behind: (1) the complexities inherent in the management of agricultural production and agricultural food chains; (2) conflicts over land and resource use; (3) government restrictions on some technologies; and (4) the challenges facing agricultural research organizations in achieving a balance between research and innovation.

Complex conditions. Agriculture is inherently complex and, to borrow words from Thomas Hardy's *Tess of the d'Urbervilles*, affected by the "persistence of the unforeseen". It is fundamentally different from industries such as manufacturing, in having to manage large environmental variability, even within a single location, as well as unpredictable challenges, such as extreme weather events and new pests or diseases. It also requires linkages between many different types of stakeholders, from farmers, who make independent choices about what they produce and how they do it, to consumers, who express their views about food production through their purchase choices. Furthermore, new agriculturally based products (such as pharmaceuticals or chemicals from crop biomass) will often have to compete with existing products with proven safety track records, or cope with new and volatile markets. The complex issues faced by many large oil and electricity companies when trying to secure sufficient crop feedstock supply for bioenergy and biofuels, within a market characterized by rapidly changing oil prices, fluctuating public acceptance and unstable policy interventions, are a case in point[6].

Conflicting demands. Concerns over potential conflicts arising from the use of land for bioenergy versus food crops, or the use of feedstocks (such as grain) for biofuels and bioenergy rather than for human consumption, have led to diametrically opposed visions in national bioeconomy strategies[3]. Some government strategies, such as those of Germany and the US, positively encourage the use of agricultural, forest and biomass crops for fuel and chemical production at a large scale — although they fall short of directly addressing issues surrounding sustainable supply[7]. Others, such as the EU and UK strategies, emphasize the use of food waste and agricultural or forest residues for these purposes. These contrasting visions reflect differences in the strength of major sectors (such as the forestry, agriculture and industrial biotechnology sectors) as well as differences in the priority given to environmental concerns, and current land-use and availability. The labyrinth of ever-changing policies and government interventions aimed at resolving such issues is not conducive for long-term investments in the agro-bioeconomy[8].

Regulatory hurdles. Many agricultural scientists, faced with issues over public acceptance of new technologies and government restrictions on using genetically manipulated (GM) crops, feel unable to capitalize on many technical advances. The increase in land area under GM crops over the past ten years constitutes the biggest adoption of an agricultural innovation so far, but regulations have severely restricted their use in many places, including Europe, and the costs involved make GM an improbable route for all but the largest companies. Newer technologies, such as genome editing, have yet to run the full gauntlet of critical examination before their deployment potential is known[9]. Such issues are not confined to agriculture, but investments in human health are larger and the benefits more directly realized, so the risks are more acceptable.

Entrepreneurial impediments. Many farmers are great entrepreneurs. Scientists within agricultural research institutes and universities, on the other hand, are often constrained by the ever-changing and sometimes conflicting expectations of governments, funding agencies and sponsors, as well as the public, when it comes to entrepreneurism[10]. Most walk a precarious tightrope to achieve a balanced research portfolio (in the eyes of their appraisers and funders) that includes the delivery of scientific excellence, strategic relevance, impact and commercial output, while also avoiding being labelled as 'no longer independent' by the tax-paying public, who ultimately fund them[11].

Cultivating cultural change

Agricultural organizations have an important part to play in contributing scientific evidence to debates in order to help overcome many of the above-mentioned hurdles in the development of an agricultural bioeconomy. Importantly, they can also change significantly their approach to innovation and entrepreneurism. Most of the published national bioeconomy strategies[2,3] recognize the need for change in this respect, and suggest mechanisms and instruments that agricultural research organizations can build on.

The need for interdisciplinary research and integration across the life sciences, with more information sharing and cooperation between the public and private sectors, and more international cooperation and knowledge pooling, is emphasized in most government strategies. The agricultural sector has a head start in this, as past trends have positively encouraged cooperation and knowledge pooling, and new initiatives (such as AgriTech, mentioned above), are already building on this approach. Also recognized in most strategies is the need for new measures that will accelerate technology transfer through problem solving and the identification of market needs. The way that the Fraunhofer Institutes in Germany work by teaming industry with research organizations to scale up cutting-edge research into working technologies on an industrial timetable is seen as a useful model by countries worldwide, and could be applied in the agricultural sector.

Most bioeconomy strategies also acknowledge the need to streamline current legislation and regulatory bottlenecks, as well as to increase dialogue with the public and to establish appropriate ethics and security platforms. The EU, for example, has created a Bioeconomy Panel to foster an open dialogue and enhance coherence among policies, initiatives and the economic sector, and a Bioeconomy Observatory to assess progress and impact. Some strategies also anticipate legal and regulatory reform. All these developments could help overcome some of the difficulties faced with the adoption of new technologies in crop breeding. The need for new approaches to the funding of research and the training of researchers to encourage innovation and entrepreneurship is also identified. The integration of translational research into academic coursework and offering training in entrepreneurism to faculty members are some of the solutions proposed.

Agricultural science has many attributes that suggest it should be able to embrace these changes and become a major contributor to the bioeconomy. It is an interdisciplinary field by nature and has a long history of technology transfer and stakeholder engagement. Transformation in farming is continual, and agricultural researchers have long grappled with the biology of hugely complex managed agricultural systems in order to make interventions. Many of the solutions developed may have applications outside of agriculture itself: smart sensing systems that report on crop health status could have applications for monitoring health of trees and other keystone species in natural ecosystems; methods based on bioremediation for managing contaminants and pollutants arising from agricultural land use could have applications in cities; plant chemistry, evolved to combat pest attacks, can be a source of novel drugs for humans; and agricultural soils could be a source of novel microbes or enzymes for industrial processes, or of antibiotics to help tackle human health problems such as anti-microbial resistance.

An agriculturally based bioeconomy, however, cannot be achieved by simply revitalizing or re-labelling individual areas of agricultural science, such as soil or crop science. Economic impact is an unremitting metric of the bioeconomy, and many agricultural research organizations will need to engender a more ideas-led and innovative culture to compete[7]. Interdisciplinary approaches involving physicists, chemists, engineers and computational biologists, as well as entrepreneurial thinking, will be crucial for success. To stimulate the generation of ideas outside the traditional agricultural box, and to introduce economic opportunities to farming and agriculture, new partners should be sought from a wide range of sectors, including device manufacturers and information technologists, and from across existing farm-to-product value chains.

The time for change is now. It is imperative that agricultural research organizations embrace the cultural changes suggested in the action plans of many bioeconomy strategy documents, and thereby the opportunities offered by the bioeconomy. There could not be a more exciting time to be in agricultural science. ❐

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