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Biosecurity and sustainability within the growing global bioeconomy

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Crop-based biofuel production has grown exponentially, driven by government policy interventions to achieve national targets and venture capital investments. This urgency may compromise the biosecurity of these and future agricultural production systems such as the development of new bioindustry-focused GM crops for high value industrial and pharmaceutical compounds. Energy security and prospects of a future emission-constrained economy are driving these developments of novel non-food crops and varieties in new areas, coupled with domestic agricultural and innovation policies and responses to recent and potential future crude oil pricing. New species and varieties are now being commercially fostered around the world also because of their potential to reinvigorate the global agro-forestry industries. The vanguard of the first, second and third generation biofuel solutions are in various stages of production. Their true dollar and carbon-based economic viability is unclear due to government subsidies along the value chain, and some crop-production systems are failing commercially and environmentally due to limited consideration of associated agronomic biosecurity problems. Novel crops in current production systems and new regions can also pose significant invasion threats to human health, agriculture, biodiversity and natural ecosystem services through firstly, uncontrolled allergen and toxicity-associated impacts on human well-being; secondly, abandoned trial plantings of uneconomic varieties; and thirdly, feral individuals (or invasive species) from economically viable plantations invading agricultural and natural landscapes. Novel crops will also have suites of pests, weeds and diseases that will impact pest management systems in neighbouring crops. To avoid this we need landscape scale sustainable integrated pest management systems that ensure the triple-bottom-line production viability requirements of the 21st century. This introductory paper summarises the new global bioeconomy and the international policy opportunities and challenges for sustainable development that it encompasses. We then introduce the biosecurity issues covered by this issue of *Current Opinion in Environmental Sustainability* from a research, policy and industrial perspective.

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The bioeconomy: biofuels and beyond

The 'Biobased Economy' first emerged as a policy concept within the OECD in 2002 linking renewable biological resources and bioprocesses through industrial scale biotechnologies to produce sustainable products, jobs and income [1]. The concept has since evolved to encapsulate all internationally relevant economic activities relating to the invention, development, production, and use of biological materials and processes driven by new knowledge and technologies [1–4,5••,6•].

The bioeconomy is shaped by a number of drivers, including:

- The rapid uptake of biotechnologies in agriculture production and processing industries.
- The demand for sustainable renewable biological resources and bioprocesses as feedstock for these new industries.
- The construction of eco-industrial clusters and technology parks that produce sustainable goods and services, jobs and income.
- The opportunity to 'decouple' industrial growth from environmental degradation through more sustainable production methods through industrial scale biotechnology.
- The need to respond to global challenges such as energy and food security with increasing constraints of water, productive land and carbon emissions.

A critical aspect of the bioeconomy is the gradual emergence of new sectors and cross-connections in the existing economy toward a new integrated economic paradigm. Already, several existing industry sectors have parallel drivers that are helping to shape the bioeconomy but these drivers will integrate over time. In general:

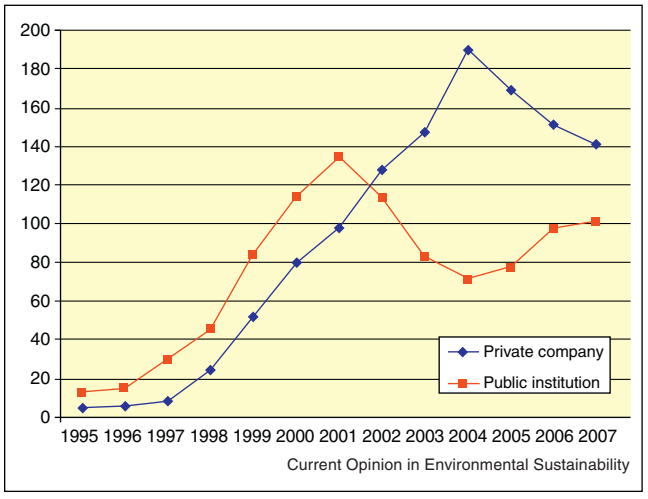
- The agribusiness sector is looking for productivity growth to enable product differentiation and high value opportunities for new markets.
- The forest products sector is looking for new opportunities to produce value-added products while securing access to emerging carbon capture markets.
- The chemical sector is looking for low-cost renewable feedstock, greener processes and products to support new manufacturing demand for sustainable materials
- The energy sector seeks low carbon solutions for stationary and transport energy.

Fundamentally, the raw materials come from organic biomass, biological residues or existing and novel crops that would be bred, but more often bio-engineered to generate large quantities of raw ingredients that could be processed and biorefined into a range of food, health, fibre, industrial products and energy, such as plastics and fuel health products and pharmaceuticals.

In 2009 the OECD published a report '*The Bioeconomy to 2030: designing a policy agenda*' [5••] to provide a policy roadmap for national economies to assist in the development of this sector and describe expected outputs and outcomes. While still relatively small, sector development is occurring rapidly and it is expected in the future to contribute significantly to the economy and society through health benefits, energy efficiency, reduced environmental impacts through enhanced sustainability and improving human welfare more generally. Agricultural biotechnology underpins the development of the bioeconomy. By 2030 the OECD report predicts biotechnology will play a role in virtually all major commercial crops and the development of nearly all drugs and pharmaceuticals. Agriculture will experience the major socio-economic effects of biotech in the mid-term with an estimated OECD market potential of US$ 680 Billion per year [7].

However, when adopting a more holistic value-chain approach linking agriculture and industrial processing, the picture becomes much sharper. Collectively, by 2030 the bioeconomy market opportunity across the OECD is predicted to see 75% of the gross value added from the combined contribution of agriculture (36%) and industry (39%), the remaining comes from the health sector. This is in stark contrast to the distribution of recent R&D investment in biotechnology with 87% to health and only 6% devoted to agriculture and industry combined. A significant shift in investment patterns will be required to capture the long-term opportunity, but this is starting to happen. Structural change to agricultural systems is needed for a number of reasons and this is already being seen in developing countries, where public sector investment has increased to create national capabilities in agricultural biotechnology. Numerous multinational companies are investing millions of dollars in technology development in this space. Several south-east Asian economies already have double digit bio-economic growth [8]. As a result the non-food agricultural sector is expected to show massive growth. This has already started for biofuel production (Figure 1).

Figure 1



The number of GM field trials of potential second generation biofuel crops (trees and grasses) in OECD countries as a three year running average. Public includes private non-profit (from [5••]).

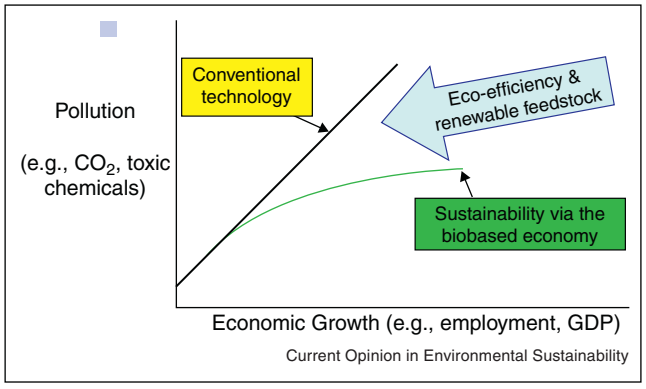
Bioeconomy driven changes to agriculture are already leading to new production systems, new crops and crop varieties that aim to generate products with benefits for the environment or human health [5••]. Such benefits, it is argued, will lead to less conservative consumer attitudes on biotechnology [9] and a re-innovation of the agricultural sector with associated economic benefits [5••]. Greatest advances are seen in biofuel cropping systems for bioenergy production, which are the greatest current bio-economical challenges driven by peak oil concerns and associated sovereign state energy security issues, climate change and prospects of future emissions constrained economies. Crop-based biofuel production has grown exponentially this century [10]. The US and EU zones have adopted national targets for biofuel use into the future and to assist this they have instigated mechanisms of government subsidy to help achieve these policy positions [11,12]. First generation biofuel crops producing starch for bioethanol or oil for biodiesel include existing crops (e.g. maize, sugar cane canola and oil palm coconut, castor oil plant, soybean peanut, sunflower, and castor beans), new oil crops (e.g. Jatropha, Chinese tallow, moringa, pongamia calotrope, agave) or new bred or GM high yield varieties of these crops [13]. Second generation biofuel crops have high cellulose yield for bioethanol production, for example fast growing grasses (giant reed, switchgrass, and miscanthus) and woody plants. It is

important to note that non-GM biotechnologies, such as marker assisted breeding, can be used with significant impact without the same consumer impact as GM technologies have, although GM technologies can be critical to reduce lignin content which currently limits conversion [13]. GM high yield macroalgae (*Chlorella* spp.) in open ponds can also produce oil and high cellulose with low lignin with production rates 10–100 times more efficient than terrestrial plants [14,15]. GM technologies should also be able to make plants express bacterial enzymes that directly convert cellulose to starch and/or starch to glucose [16•,17]. Beyond biofuels GM is also being used to produce specific industrial compounds (e.g. pharmaceutical products or non-edible oils for biodegradable plastics) taking one stage further what are increasingly being termed bio-factory plants [18,19•,20•].

Once the plant biomass (in whichever form) has been generated, industrial-scale biorefineries convert it into a full range of products (including co-generation of energy) and pilot biorefineries have already been developed in the USA and Europe [21]. Efficient and viable productions systems will require firstly, consistent low-cost year-round feedstock supply technology; secondly, integrated biorefineries for simultaneous production of multiple complementary products with contrasting market values to ensure economic sustainability; thirdly, maximum feedstock utilization and minimum waste; fourthly, robust and credible environmental regulation, incentives and credentials; and fifthly, a mix of private investment and public policy and incentive to build consumer demand. For low value biofuel production systems public sector funding is both needed and forthcoming [22].

In order to deliver new industries, sustainability, green jobs and the benefits from the future products it can deliver, the bioeconomy and associated transformations to agriculture face a number of challenges around proven environmental credentials, meeting market feedstock demand and price [22], avoiding competition with food production around land use, preventing further direct degradation of biodiversity assets and clean water supply [23] and the novel biosecurity risks associated with new crops and cropping systems [24••]. Such innovation in the 21st century must also be eco-efficient, where increased economic growth is achieved using renewable resources and without increased environmental pollution (Figure 2).

Figure 2



The bioeconomy needs to decouple the historical relationship between economic growth, energy use and environmental degradation (from Dr John Jaworski presentation to the 2003 International Energy Agency Workshop 'Promoting international collaboration in energy efficient bioprocesses', Ottawa, Canada).

The sustainability debate

The sustainability of bio-based production systems has been under intense scrutiny particularly for biofuel production to viably contribute to future bioenergy needs for replacing non-renewable energy sources and to ensure future energy security [23,25,26]. It is highly desirable that the whole of life cycle carbon footprint of bio-based production systems should be much less than petro-based equivalents for the same products [27••]. USA and EU binding targets for biofuel-based energy production [11,12] are supported by subsidies for production and purchasing all along the value chain. The EU aims to achieve 7% of liquid fuel needs from biofuel production systems, which, based on averaging 15 science studies made for the European commission, Reuters estimated would require about 4.5 Million ha within its borders [28]. Similarly, New Zealand would need to allocate 1.8 Million ha of plantation forest to provide the cellulose for 65% of current liquid transport fuel demands [29]. Competition with food production will require a substantial part of these bio-energy requirements to be imported in many developed countries [30]. This has led to a hot both scientific and political debates about impacts of clearing the extra land required for this level of biofuel production [31,32••], which would more than counteract any carbon benefits. Governments have been accused of setting unsustainable biofuel production targets before the science had been fully understood [23]. Meanwhile proponents of algal bioenergy production systems argue that from an efficiency perspective these could meet global demand more easily than field crop-based bio-energy production systems [33].

Competing food and non-food production systems and the impacts this may have on food security is at the core of the debate [32••,33]. With growing global populations, food production has to double to meet global population projections over the next 40 years [34]. Changing demographics also alter the nutritional demands of increasing populations as developing economies provide a broader demand for a meat based diet [35]. In addition to increased demand, limits in land, water and petrochemical-based and phosphorous fertilisers will lead to increasing food prices [33]. Annual percentage increases in food crop productivity are in decline too (from 3% in 1960s to 1–2% per annum 2005 — OECD-FAO statistical database) limiting capacity

to compensate for increasing demand. There is an indication, however, that reduced productivity gains may also be linked to declining investment in agricultural R&D [36]. Increasing food prices will at least encourage growers to switch away from non-food low value alternatives like biofuels, ensuring some balance to competition for land use between food and non-food agriculture.

Given the immediate land use demands for biofuel crops, the potential for indirect impacts of a growing non-food agricultural sector on the environment and the services humanity gains from this has also been widely recognised [23,37•,38]. Impacts not only on carbon debt, but also on biodiversity and associated ecosystem services like high quality water supply have all been identified and will become more acute as the bioeconomy expands [39•]. The need to make sure adequate policy protections are in place has also led to policy changes in the USA and similar changes are likely to take place in the EU [23]. There has also been valuable discussion about the concept that to avoid competition with food production, biofuel crops could take more advantage of idle, marginal or lower productivity lands. There may be instances where the use of such land could provide benefits. An example of this could be the expansion of existing plantation species onto marginal grazing land where a forestry-based biofuel crop could deliver improved environmental services on a sustainable basis. Careful planning is needed, however, as ecologists and economists are agreeing that an *ad hoc* advocacy for marginal land use can have many negativities [23,39•]. Marginal land exploitation more generally poses increased threats to ecosystem services and biodiversity in remnant communities therein as well as reducing profitability and hence viability of production systems to the point where, particularly in developing countries, 'slash and burn' rather than sustainable agricultural practices are likely to predominate [31,32••,40].

It is now widely recognised that international bodies and international cooperation, especially between the developed and the developing world, will be required to increase sustainability in a complex market place of strong food and non-food sectors [34,35].

Biosecurity — an ignored concern

Despite strong recognition of some of the broader sustainability issues, surprisingly some of the threats of direct impacts of the new crops themselves and the pests they may harbour do not yet appear to be receiving the same level of attention in the broader sustainability. The promulgation of new biofuel species recognised as having characteristics linked to invasive capacity has been discussed in the science literature [24••,41•,42,43] and highlighted in a few reports directed at the public and policy makers [39•,44,45•,46], but has not yet been recognised explicitly at the policy level. Accurately predicting which new plant species will become invasive is not always possible [47••]. Nonetheless an increasing number of science-based screening systems, including regression trees, Bayesian belief networks and nested sieve approaches are being developed [41•,43]. Weed risk assessment systems have now been applied around the world and shown to significantly decrease the odds of deliberately introducing a likely invader [48].

We believe these future threats posed by a large new non-food agricultural sector driven by the bioeconomy have not been given adequate thought or acceptance by industry and policy makers and in many cases have gone ignored. Every agricultural revolution has led to whole suites of new biosecurity risks leading to harmful impacts on the environment, agricultural economics and human health. This usually results not only from the side effects of deliberate introduction and or mass plantings of failed trial crops which turn feral and suppress biodiversity and degrade ecosystem services, but also from the pest species they can harbour [47••].

By biosecurity we are referring to protecting the integrity of each nation's biological resources (agricultural production, biodiversity and ecosystem services), along the 'biosecurity continuum' from pre-border pre-emption and preparedness for future biological threats to post border management of existing exotic invasive pests [49]. With the deliberate planting of new species into new areas biosecurity considerations should also include the spread and impact of native species outside their normal ranges. This definition is deliberately narrower than usage that can include pre-meditated introductions for bioterrorism (WHO), and managing access to biological materials that could be weaponised without inhibiting cooperation and trade (OECD). In our context here, however, biosecurity also includes potential impacts of biological invasions directly and indirectly on human well-being.

The development of GM technologies in agriculture has led to concerns that engineered genes will allow volunteer crops to persist in the environment [50] and potentially have negative impacts, or that such genes would transfer to wild genotypes causing genetic pollution into native ecosystems [51]. Similar concerns need to be satisfied for new non-food crops used in the development of the bioeconomy. New crops will also have new pests that require new pest management systems for both these crops and any existing crops that may also suffer from these new pests through changes in agricultural landscapes. This issue of *Current Opinion in Environmental Sustainability* will focus on the new types of non-food cropping and forestry for biomass production and the biosecurity issues associated with them.

As the field leader, biofuel crop production, driven by government urgency, has largely ignored the inherent

biosecurity risks that could compromise current and future agricultural production and natural ecosystems. Indeed different government directives around bio-energy development and environmental protection have led to conflicting goals [43]. Biosecurity issues will also continue to appear alongside future entrepreneurial development of new bioindustry-focussed conventional or GM crops for high value (industrial and/or pharmaceutical) compounds. The new species and varieties being commercially fostered around the world to develop and reinvigorate the global agro-forestry industries and to meet energy security needs are not all proving to be successful business ventures. There are successes where the expansion of existing forestry activity, and well understood pest management systems, onto overgrazed or weed infested lands is leading to net environmental and carbon storage benefits. Many novel crop production systems that have been introduced into new areas, however, have failed commercially and/or environmentally. There are generally two reasons for this. Firstly highly successful commercial crops like oil palm can create too great a temptation to clear native forest to expand production [52]. Secondly, a failure to consider the necessary growth conditions for such crops or the likely scale dependent pest and disease threats has resulted in poor and uneconomic crop yields [53].

Such new crops can lead to allergen issues (e.g. certain plantation trees [54]) or human toxicity residues that may be ignored in the race to production [55]. When these systems prove uneconomic because of environmental, pest constraints or simply poor business development, abandoned plantings persist in the landscape to spread with no industry or regulatory/government agency capacity to manage these future threats. Nonetheless these risks have to be balanced against the potential economic and social benefits such new agro-forestry systems may offer. Simply applying risk-based evaluation system for the introduction of new plant species may soon no longer be socially justifiable. There remains a challenge, however, because potential benefits may be quite easy to quantify in dollar terms, while the long-term risks and associated costs are not and will have higher uncertainties. Systems are being considered [43], but more needs to be done to provide science-based whole of industry evaluation systems for these new crop species.

Novel crops will also have suites of pests, weeds and diseases that can not only impact on pest management in neighbouring crops, but also will require landscape scale integrated pest management technologies to ensure their own triple bottom line production viability. As such, novel crops will offer enormous opportunities to apply pest management science in current cropping systems to rapidly develop sustainable strategies and profitability to these new industries.

In this paper we have introduced the topic of the bioeconomy and the sustainability debate that has developed around the growing biofuel sector. From this we delved into a more detailed assessment of the biosecurity issues facing the bioeconomy, which have had much less exposure within the broader sustainability debate and therefore is the selected focus of this issue of *Current Opinion in Environmental Sustainability*. The papers that follow review how biosecurity issues need to be considered when developing the bioeconomy in a variety of ways from feral crops to new pest problems. The aim of the issue is to explore how research can inform policy and help address the economic, social or environmental biosecurity challenges that the bioeconomy will need to address.

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