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Reconciling Food and Industrial Needs for an Asian Bioeconomy: The Enabling Power of Genomics and Biotechnology

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Abstract: While bioeconomy as a concept has been used by many countries in the world in policy and strategy development not many countries in Asia have used this concept. This paper discusses how Asian countries can use biotechnology and various omics technologies to address their pressing problems and develop strong bioeconomies. The paper explores the potential and limitations for using different technologies in Asia and points out that as these technologies can be applied in different sectors ranging from aquaculture to forestry. They will enable Asia to meet the problems in effective utilisation of biomass and address critical problems like food security. These applications will result in economic gains and better returns on investments. While the potential to reconcile industrial production with food needs is yet to be fully realised as these technologies can enable better utilisation of waste and related biomaterials by turning them into feed stocks, they provide many opportunities to Asian countries in meeting diverse needs and reconciling multiple demands from similar resources. Application of biotechnology, omics technologies, synthetic biology and green chemistry can be the enabling technologies for the biorevolution that may usher in better bioeconomies in Asia.

Keywords : omics technologies, bioeconomy, Asia, food security, biomass

1. Introduction: Why A Bioeconomy in Asia?

In a previous paper for this journal (Philp and Pavanan 2013) some of the basics of bio-based production in relation to sustainable development in Asia were explored. In this paper, we take up the theme again, but in

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a wider bioeconomy context – the need to reconcile food and industrial production from biomass(Jiménez-Sánchez and Philp 2015). This is perhaps the critical issue in a bioeconomy, and it is in sharp focus in Asia. South East Asia, for example, is quite different in bioeconomy terms from many developed economies with regard to biomass. A large amount of global biodiversity resides in some countries of South East Asia, much more so than in many OECD nations. Nevertheless, they have a similar deeply complex problem to wrestle with – how to economically exploit this biodiversity and biomass in a sustainable manner that does not cause unintended social and environmental problems.

Since the OECD (2009) publication, *The Bioeconomy to 2030: Designing a Policy Agenda*, several countries and regions have responded with bioeconomy strategies, among them Belgium, Canada, Denmark, Finland, Germany, Ireland, the Netherlands, Sweden, the United States, the European Union and South Africa, many foreseeing a gradual replacement of fossil-derived materials with bio-based.Now, key objectives for a bioeconomy are embedded in the strategic activities of more than 30 countries. Very few Asian countries have followed suit. A notable exception is Malaysia (Bioeconomy Malaysia 2014), which has produced a plan for a very ambitious bioeconomy (see Box 1). Japan does not formally have a bioeconomy strategy (Bioökonomierat 2015), but has many policies consistent with a desire to build a bioeconomy.

In everything from research and development to full-scale implementation and biomass production, Asian countries are likely in the long-term to be leaders in bio-based production. With growing commitments to climate change mitigation, Asia can reap the benefits of economic growth, jobs and environmental improvements that bioeconomy promises. But careful international co-ordination and co-operation will be necessary.In addition, many of these Asian economies have a very different agricultural model from most OECD countries. The value added per agricultural worker tends to be much lower than in the OECD, and farmer ageing and poverty are central issues in food security. Perhaps the trend can be mitigated or reversed by participation in a global bioeconomy.

Long ignored as a potential engine of economic growth, modern biotechnology has many benefits to offer, both in food and industrial production. The case is made that, even without genetic modification, genomics and other -omics technologies can solve scientific, environmental and economic problems in relation to the bioeconomy, and it can also be argued that there are follow-on social benefits that are pertinent to Asia beyond the obvious job and wealth creation benefits.

Box 1: The Malaysian Bioeconomy Strategy

Malaysia launched its Biotechnology Transformation Programme (BTP) in 2012 as part of the nation's economic transformation strategies. To do so, Malaysia is providing an incentivised platform for the bio-based industries to contribute to its sustainable development agenda, to improve industry competitiveness, to encourage public-private partnerships and bring socio-economic benefits. The initiative is supported by public sector stakeholders such as universities and research centres, economic corridors, financial institutions and inter-ministerial coordination.

Some Early Targets for the Malaysian Bioeconomy

The early targets to 2020 and those beyond are ambitious. Malaysia expects by 2020 a contribution of: US$ 15 billion to GNI; the creation of 170,000 jobs, and investments of US$ 16 billion. For comparative purposes, by 2020 the bioeconomy is expected to contribute 8-10 per cent towards Malaysia's total gross domestic product (GDP), from the current 2-3 per cent.Malaysia expects to achieve this ambitious target by a transition towards higher value downstream activities.

The Strategic Position of Biomass in Malaysia

Malaysia is one of the world's 17 megadiverse countries. It, therefore, has a rich source of biodiversity to tap into to support of its bioeconomy. A large amount of biomass is generated every year across a variety of crops such as palm oil, rubber and rice. Within this sector, by far the largest contributor to GNI is palm oil, contributing about 8 per cent to the national income. While the opportunity is immense, palm oil biomass is also utilised for a variety of additional higher value uses including wood products, energy pellets, bioenergy, biofuel and bio-based chemicals. By year 2020, Malaysia's palm oil industry is expected to generate about 100 million dry tonnes of biomass. This includes empty fruit bunches (EFB), mesocarpfibres (MF) and palm kernel shells (PKS) as well as oil palm fronds and trunks. Moreover, oil palm is only part of the Malaysian bioresource. Other examples are timber waste, paddy waste, coconut trunk fibre, sugarcane waste, kenaffibre.

Box 1 continued...

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Secured Major Investments in Malaysia Demonstrate a Shift Towards Higher Value Markets

Initiative	**Partners**
Application of biotechnology for lobster aquaculture	Darden
High value chemicals from non-food based, renewable feedstock	Verdezyne
First commercial bio-isobutanol plant in Asia	Gevo
Bio-isoprene production from crude glycerine	GlycosBio
World's first bio-methionine plant and Asia's first thiochemical platform	CJ, Arkema
Integrated biorefinery project	Genting, Elevance
Regional hub for manufacture of biopharmaceuticals and injectables	Stelis Biopharma
Biopharmaceutical manufacturing and development facility	Biocon

Source: Kamal (2015).

2. The Perfect Storm: The Convergence of Key Grand Challenges

> "*Grand Challenges priority should be to address global inequalities; secondly how to rapidly decarbonise the global economy. The world needs to save the biosphere as well as the banks!*"
>
> — Anthony Costello[1]

At this point in time, several societal grand challenges are interacting with each other to create one of the most difficult periods in human development. Because these grand challenges are truly global, one of the main problems has been achieving consensus of action across countries with different starting points and levels of economic development.

The key to the enormity of the challenge is in the word 'interacting'. Food and water security obviously interact with each other, and measures to improve the security of one may negatively affect the security of the other. Therefore, the challenges are of a planet-wide nature that interacts very much like a global ecosystem (see Box 2).

Box 2: The Grand Challenges Ecosystem

> "*In an era of increasingly pervasive human influence on physical and biological components of the Earth system, what are the most effective strategies for maintaining the integrity of natural systems and the services they provide?*"(NAS 2010).

Whenever humans intervene in a system, from the level of genetics to whole community, all the way to globally, there are interactions with other components of the system, and new consequences. The 'behaviour' of these grand challenges is assuming characteristics of an ecosystem: an intervention in one location results in changes there but also elsewhere. Single human interventions are unlikely to work. There are some such interactions that are quite clear. There will be many more that are subtle and unforeseen.

Growing more crops on more land, or increasing the productivity of crops on the existing land addresses food security, but maybe only temporarily. This strategy is likely to negatively affect soil health, and will require more water, which is already stressed in many locations. It may decrease biodiversity. And people still want wild places to visit (e.g. national parks). Higher yields will require more artificial fertilisers, which mean more emissions and agriculture becoming even more dependent on the fossil industry. More agro-chemicals can lead to further pollution while production increase reaches a maximum that cannot be further increased. Bioenergy, biofuels and bio-based materials produced from biomass instead of fossil resources addresses GHG emissions reductions, central to the mitigation of climate change. But this requires more biomass, which can impinge on food security, and can interfere in many of the ways highlighted above. The interferences can partly be ameliorated by, say, using algae as a source of biomass, or using waste industrial gases as the feedstock for fermentations. Deliberately increasing the production of algae, or removing existing stocks unsustainably, inevitably affects other parts of the marine ecosystem, and may interfere with local, traditional industries and practices. It could be that the best locations for growing, harvesting and processing algae are not served by infrastructure, such as road and rail transport. The costs of developing marine biotechnology to an extent that will significantly address global challenges are very high, so a lot of attention has to be paid to consequences.

Faced with constrained finances, the policy challenges are long-term and there are no quick fixes. Ultimately the goal is interacting solutions to interacting grand challenges. This calls for multi-disciplinary research and systems innovation. There is no simplistic technological fix, and genomics

Box 2 continued...

Box 2 continued...

is merely one part of the jigsaw. But it is a very important part because genomics can offer interactions. Many of the on-going R&D activities in crop science make some of these interactions foreseeable. For example, the combination of drought/heat tolerant traits with the ability of a plant to make its own fertilisers addresses several grand challenges: water security, food security, resource depletion, climate change. Unfortunately, creating such a crop is a gargantuan task. Therefore, although genetic modification and gene editing offers the possibilities to address many of the ambitions ahead, negative interactions have to also be considered, not least of them the possible public reaction to such a strategy.

2.1 Human Population Dynamics: Asymmetry and Uncertainty

Ultimately, there is huge uncertainty about what the eventual equilibrium number of people alive will be, and when it will occur. It is expected that there will be over 9 billion people living on the planet by 2050. The implications for Asia are different than for Western countries due to demographics. For many European nations the ratio of European working people-to-elderly is changing quickly (Carone and Costello 2006): in Denmark, for example, the ratio will change from currently 4:1 to 2:1 by 2050 with serious economic consequences (IMF 2008). The ageing of populations will have large repercussions for OECD labour markets, economic growth, and public finances. The population of the more developed regions is expected to change minimally, passing from 1.24 billion in 2011 to 1.34 billion in 2100, but with the population inexorably ageing.

Meanwhile, 95 per cent of the burden of population growth will be in developing countries (UNDESA 2011). Across Asia population growth is also asymmetric. By 2021, the population of India is likely to surpass that of China and the two will account then for about 36 per cent of the world population. However, China and India have experienced a rapid fall in the average number of children per woman. These Asian giants are also ageing, and as life standards improve, this phenomenon is expected to become even stronger. By 2100, India is projected to have 130 million persons of age 80 or over, and China 107 million. Together the Indian and Chinese over sixties accounted for 34 per cent of the world population in 2011 and they are expected to constitute 38 per cent by 2050 (Chatterji *et al.* 2008; Kowal *et al.* 2012).

In East Asia several countries, like in Europe now have very low levels of fertility, well below their 'replacement rate', meaning that their populations are ageing even more rapidly and these countries face great challenges in how to care for and support these ageing populations. Projections by the Japanese government indicate that if the current trend continues, the population of Japan will decline from about 127 million in 2014 to about 97 million in 2050 (National Institute of Population and Social Security Research 2012), a phenomenon which has been termed Japan's "demographic disaster".[2]

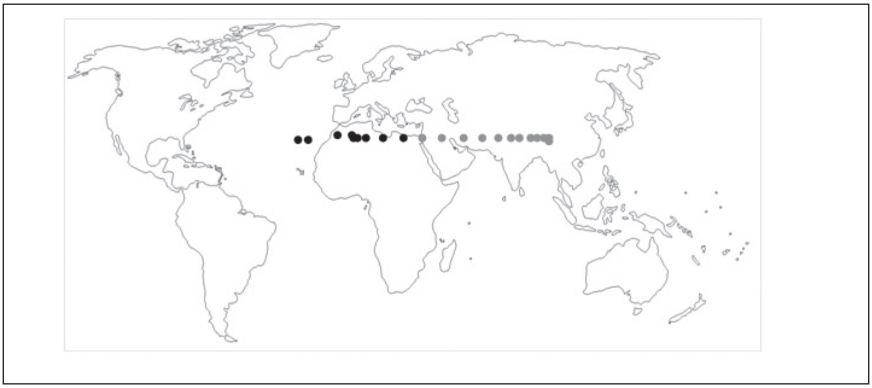
Growth of the Asian Middle Class

Of particular relevance to this paper is the predicted growth of the Asian middle class. As of 2010, Asia accounted for less than one-quarter of today's middle class.[3] By 2020, thisshare could double due to a large mass of Asian households having incomes that currently position them just below the global middle class threshold. More than half the world's middle class could be in Asia and Asian consumers could account for over 40 per cent of global middle class consumption (OECD 2010). Globally, the middle class could increase to 4.9 billion by 2030, with 85 per cent of the growth coming from Asia.

2.2 Shift in the Global Economic Centre of Gravity

The economic centre of gravity (the average location of economic activity across geographies on Earth) is moving towards Asia (Figure 1). By 2010 Asia accounted for 34 per centof global activity, but by 2034 it could account for 57 per cent of global output (OECD 2010). Not only China, India, Korea and Japan will lead this shift, but other large countries like Indonesia, Thailand, Malaysia and Vietnam will have significant economic mass. With a growing middle class and wealth comes growth and consumption, and with growth comes several environmental costs, e.g. increased greenhouse gas (GHG) emissions. A primary objective of an Asian bioeconomy should be to decouple growth from GHG emissions.

Figure 1: Shift in the Global Economic Centre of Gravity



Source: Redrawn from CNN (2011).http://globalpublicsquare.blogs.cnn.com/2011/04/07/worlds-center-of-economic-gravity-shifts-east/

Note:The global centre of economic gravity has shifted east over the past 30 years (black dots), and could well shift even farther east over the next 30 years (grey dots).

2.3 Food and Water Security versus Land Limitations

With so many more people alive by 2050, food and water security becomeincreasingly important. With over nine billion alive by 2050, food production will need to rise by 50-70 per cent (UN FAO, 2009).[4,5] More arable land, or more efficient use of existing arable land, will be needed to meet the food demands, while less may be available because of changing climate conditions. Using more land for production also impacts biodiversity.With much of the growth in population and economic output in Asia, these challenges are all the more acute. Moreover, developing countries have changed dietary patterns. In about the last 30 years meat consumption in developing countries has doubled, and egg consumption has quadrupled. The demand for more meat has significant environmental implications. Beef production is notoriously costly in resources such as water and land, and is also responsible for high GHG emissions compared to some other forms of animal protein. For every kilogram of beef produced, 4-5 kilograms of high energy feed are required, and well over 10,000 litres of water is consumed.

As many as two billion people rely directly on aquifers for drinking water, and 40 per cent of the food in the world is produced by irrigated agriculture that relies largely on groundwater. Globally, 70 per cent of all freshwater use is for agriculture (Sophocleous 2004). Vast territories of Asia rely on groundwater for 50-100 per cent of the total drinking water (UNEP 2003)and groundwater depletion is accelerating worldwide. Some of the highest rates of depletion are in some of the world's major agricultural centres, including North West India, NorthEast China, and NorthEast Pakistan (Wada *et al.* 2010). Also climate change is projected to decrease freshwater availability in Central, South, East and South East Asia, particularly in large river basins. With population growth and increasing demand from higher standards of living, this decrease could adversely affect more than a billion people by the 2050s. Asia has 28 per cent of the world's freshwater resources (UN FAO 2003) but is using 50 per cent of the world's water (Gore 2013).

2.4 Energy Security and Resource Depletion

Most countries are plagued by energy insecurity as a result of the geography and geopolitics of fossil fuel production. Many of the larger economies within the OECD import most of their oil and gas, much of it from countries and regions that are regarded as unstable. A greater proportion of crude oil in future will be from unconventional sources such as tar sands and the deep subsea. These sources are much more expensive and dangerous to exploit. The current price fluctuations do not change the fundamentals and higher prices are most likely to return in the future. Low prices inhibit investment in alternative energies, but also in conventional exploration. There is also a looming danger that prices rebound way beyond what is desired after a slump, causing large detrimental effects on the global economy.

Some Asian countries typify the energy security dilemma. Thailand is highly dependent on crude oil imports, accounting for more than 10 per cent of GDP (Siriwardhana *et al.* 2009). Energy security and rural and economic development led to Malaysian R&D on biodiesel derived from palm oil as early as 1982. Korea has similar needs, as the country imports 97 per cent of its energy, which still comes from fossil fuel reserves. Korea aims to replace 30 per centof fossil fuel with biofuel to become more energy independent. To achieve this Korea has an important programme to develop biofuel from algae. Likewise, China also has a huge demand for crude oil that cannot be met through domestic production, but faces limitations in sacrificing food security for energy. Recently, India has turned to bio-based energy to reduce dependence on imported oils. India has to import approaching 80 per cent of its crude oil requirements (Ministry of Petroleum and Natural Gas, Government of India 2009). India leads the way in planting and cultivating the non-food Jatropha plant on an industrial scale for biodiesel production (Wonglimpiyarat 2010).

No country illustrates the situation better than Japan, the world's third largest economy which is just 16 per cent energy self-sufficient.[6] Japan is the world's largest importer of liquefied natural gas (LNG), the second largest importer of coal and the third largest net importer of oil. Japan relied on oil imports to meet about 42 per cent of its energy needs in 2010 and to feed its vast oil refining capacity (some 4.7 million barrels per day at 30 facilities as of 2011), and relies on LNG imports for virtually all of its natural gas demand. Japan consumed an estimated 4.5 million barrels per day of oil in 2011, whilst it produced only about only 5,000 barrels per day (OECD 2014). Since the oil crises of the 1970s, the Japanese government has embarked on national projects in developing alternative energy resources, including raising productivity of bioethanol production.

Beyond fuels and bioenergy, however, bio-based materials offer unique economic and environmental opportunities. Bio-based chemicals usually have higher value-added and create more jobs than either biofuels or bioenergy. As climate change legislation becomes more stringent, the pressure to find new forms of manufacturing, without sacrificing lifestyle, will increase. Bioplastics illustrate the situation very well. Plastics are the most successful materials of all time, but they have come to create environmental problems, such as a landfill dilemma and large quantities of GHG emissions associated with their manufacturing. Plastics are, and bioplastics promise to be, extremely important in Asian economies (see Box 3). Bioplastics, using biomass instead of crude oil as the feedstock, represents a huge economic as well as climate change mitigation opportunity. By using biomass, there could be significant gains in energy security also: around 7-8 per cent of the oil barrel is used in current production of plastics (as feedstock and energy source). By 2050 plastics consumption could quadruple, putting enormous strain on crude oil utilisation and the need to discover more new oilfields.

Box 3: Bioplastics and Asia

Thailand is an interesting test case for bio-based production. Thailand has more than 4,000 companies in the petro-plastics industry, and is also very rich in biomass (Ministry of Science and Technology of Thailand 2008). Since 2006, the Thai Government has declared the bioplastics industry to be one of the strategic industries that the government is promoting in its drive towards sustainable growth and development. This resulted in 2008 in a *National Roadmap for the Development of Bioplastics Industry*, developed by the National Innovation Agency (Ministry of Science and Technology of Thailand, 2008). This action plan for 2008-2012 was focused on four main strategic areas:

- Sufficient supply of biomass feedstock;
- Accelerating technology development and technology co-operation;
- Building industry and innovative businesses; and
- The establishment of supportive infrastructure.

Several Asian countries (e.g. Malaysia, Japan, Korea, Singapore and China), offer attractive tax reductions to companies that want to research and invest in the bioplastics sector (OECD 2013c). Both Japan and Korea have well-developed policy frameworks for the development of bioplastics industries.

The mitigation of resource depletion objective of developing a bioplastics industry is exemplified by Japanese policy. Following the ratification by the Japanese Government of the Kyoto Protocol in June 2002, the Government announced (December 2002) two measures: the *Biotechnology Strategic Scheme* and the *Biomass Nippon Strategy*. The main objective of the two measures was to promote the utilisation of biomass and to reduce the consumption of fossil resources and to mitigate global warming through the use of biotechnology. The policy objective stated in the *Biotechnology Strategic Scheme* is to replace approximately 20 per cent (2.5 to 3 million tonnes per year) of conventional plastics with plastics from renewable resources by 2020. This stimulated some major Japanese corporations into sourcing bioplastics for their products, e.g. Toyota.

Similarly, in 2012 the Korean government announced a *Strategy for Promotion of Industrial Biotechnology*, with the goal of establishing a mid- to long-term strategy to develop related technology and devise detailed measures for implementation, contributing to lowering the existing dependence of the economy on crude oil. By 2020, this effort is expected to result in replacing 4.8 per cent of crude oil imports with biochemical product manufacturing, reducing CO_2 emissions by approximately 10.8 per cent, and generating at least 43,000 new jobs.

2.5 Climate Change and Global Warming

UNEP (2010) calculated that a doubling of wealth leads to an 80 per cent increase in emissions. An objective of building a bioeconomy is to break this vicious cycle so that economic growth can be achieved without increasing the threats of climate change induced by greenhouse gas emissions.

To date 167 countries have signed up to the Copenhagen Accord[7], in trying to limit the temperature rise, compared to pre-industrial levels, to 2ºC by limiting greenhouse gas emissions from fossil resources. And yet, taking into account the impact of measures already announced by governments to improve energy efficiency, support renewables, reduce fossil fuel subsidies and, in some cases, to put a price on carbon, the world seems on a trajectory consistent with a long-term average temperature increase of 3.6°C (IEA 2013).

Theimplication of limiting the greenhouse gas effect is that most of the known and projected fossil fuel reserves may be unburnable(Meinshausen*et al.* 2009; Carbon Tracker 2013). This has recently been quantified: a third of oil reserves, half of gas reserves and over 80 per cent of current coal reserves should remain unused from 2010 to 2050 in order to meet the target of 2°C (McGlade and Ekins 2015). Moreover, achieving a 2°C scenario means only a small amount of fossil fuels can be burned unabated after 2050. In the view of Friedlingstein *et al.* (2014), two thirds of the CO_2 emission quota consistent with a 2°C temperature limit has already been used, and the total quota will likely be exhausted in a further 30 years at the 2014 emissions rates. By century end, the IPCC (2014) has warned that GHG emissions need to be close to zero to achieve the 2°C obligation.

Many of the worst effects of climate change are expected to affect developing nations. This includes a large number of Asian countries. Bangladesh, for example, is a 'frontline state' of climate change[8], predicted to be one of the first and the hardest hit countries to face the adverse impacts of warmer global temperatures, e.g. glacier melt, increased flooding from the sea, very often accompanied by outbreaks of infectious diseases.

A cruel irony of climate change is that many of the countries that desperately need to develop their economies will in future have to do so without fossil fuels. A second irony is that climate change has been caused by the nations that have developed through exploitation of fossil fuels. Therefore, there is a clear need for international cooperation in the development of a global bioeconomy – many of the developed nations lack biomass, and many developing nations can provide biomass. But these latter nations will benefit much more from developing a bioeconomy in which they combine biomass exports with a home-grown, knowledge-based and biotechnology-driven bioeconomy.

Drought, Temperature and Crop Yields

Agricultural productivity is ultimately defined by crop yield. Elevated temperatures have long been known to affect plant growth. Schlenker and Roberts (2009) demonstrated for three major US crops that an increase in temperature above the optimum for each resulted in a very rapid decline in yield. Their modelling suggested that average yields could be predicted to decrease by 30–46 per cent before the end of the century under the slowest warming scenario and decrease by 63–82 per cent under the most rapid warming scenario. The US Environmental Protection Agency (EPA) has predicted that by mid-21st century, crop yields could increase up to 20 per cent in East and South East Asia. In the same period, yields could decrease up to 30 per cent in Central and South Asia.[9]

The US has just experienced its most widespread drought in more than half a century (Reardon and Hodson, 2013), and the drought in 2014 in California was perhaps the worst ever recorded (*National Post*, 2014). In 2015, for the first time in decades, officials in California have forced thousands of farmers to reduce water use.[10]In Brazil, the three most populous states are currently experiencing their worst droughts since 1930.[11] As agriculture accounts for around 70 per cent of all fresh water use, measures that conserve water are of the utmost social and economic importance.

High temperatures in many cases can be expected to be accompanied by drought conditions. Evidence suggests that heat and drought stress can cause disproportionate damage to important crops compared with either stress individually (Atkinson and Urwin 2012). Therefore, improvement of dual stress tolerance to heat and drought in crop plants has become a top priority for the development of agricultural biotechnology for both food and bioenergy markets.

2.6 Soil Destruction

Often overlooked in policy making, soil is the ultimate genetic resource; soils are the critical life-support surface on which all terrestrial biodiversity depends. More than 95 per cent of all food is derived from cropland (Gore 2013). But soil is being destroyed at unprecedented rates due to soil erosion (e.g. through deforestation), pollution, desertification and salination. About 2.5 per cent of arable land in China is too contaminated for agricultural use (Chen and Ye 2014). In terms of the number of people affected by desertification and drought, Asia is the most severely affected continent[12], with the largest area under eroded drylands condition (Ma and Ju 2007).

It takes around 500 years to form 25 mm of soil under agricultural conditions, and about 1,000 years to form the same amount in forest habitats.[13] Therefore, soil should be treated as a non-renewable resource. In the bioeconomy and sustainability context, soil accounts for some 20 per cent of the capture of human CO_2 emissions (European Commission 2007). The message is clear – our society is utterly dependent on maintaining the global stock of healthy soil. Any plans for a future bioeconomy dare not ignore this. An increasing rate of soil degradation must be reversed. In the face of soil destruction, more crops will have to be grown more efficiently, while methods should also be explored to halt or limit soil destruction.

3. What Can Biotechnology and Genomics Offer?

The potential of the modern genomics technologies, when allied to more traditional genetic engineering, is so great that most of the applications are as yet not thought of. For a continent as vast as Asia, it is beyond the scope of this paper to cover the potential in detail.

3.1 Selection or Genetic Modification?

Although very powerful, it should be stressed that genomics does not necessarily involve genetic modification (GM) or synthetic biology, and the negative societal issues that have haunted GM in many applications can be avoided. Rather, -omics technologies can be applied to animal and plant breeding to greatly improve the efficiency of selection of traits. In the case of trees, this is especially important given the long timescales needed for tree growth and trait expression.

To use the full potential of genomics there is a need to link genomics information to phenotypic characteristics. The availability of well-defined linkage maps and the extent of genetic studies conducted on them vary among different crops, and this influences the feasibility of any Marker Assisted Selection (MAS)[14]-related activity. MAS allows to reduce the breeding cycle time significantly (e.g. for cassava from five to two years) and is much more accurate (Ly *et al.* 2013).

The yield increase of the so-called green revolution in modern agricultureafter the Second World War is flattening out. In addition, current agricultural practices with higher inputs, such as pesticides and fertilisers to ensure high yields, are not considered environmentally sustainable. For further yield improvement of commonly used crops or for so-called orphan crops, the use of advanced breeding methods, using MAS and increasing germplasm will be essential. Today many orphan crops have not yet been pushed to their limits and will still benefit from traditional and advance breeding.

3.2 Crop Genomics

There are many applications of genomics and genetic engineering/synthetic biology to increase crop production that will be utilised in the future bioeconomy, e.g. pest resistance, more "efficient" plants that use less water, resistance to environmental stresses, the development of crops that can fix nitrogen to replace synthetic fertilisers or change C3 plants into C4 plants.[15] Heat and drought stress are used as examples of the potential of the application of genomics to agriculture. On the other hand, too much water can also lead to crop destruction.

Dual Heat and Drought Tolerance

Genomics can be used in conjunction with either modern techniques of plant breeding or genetic engineering to improve the accuracy and efficiency of selection. For example, the most obvious dilemma for agriculture posed by climate change is the dual stress of heat and drought. A subset of target genes that constitute a novel transcriptional regulatory cascade that controls plant responses to the combined stress has been identified (Huang 2013). In laboratory conditions, *Arabidopsis* and canola plants with mis-sense expression of these regulatory genes were able to tolerate independent higher temperature or drought treatment. More importantly, these plants produced higher seed yield comparing to their controls when both stresses were applied simultaneously. The dual stress tolerance and yield enhancement properties of the transgenic plants were further confirmed by large-scale, multiple season and location field trials. These results represent a significant breakthrough in crop improvement and technologies derived from this research could enable farmers around the world to maintain higher yield and productivity over variable and adverse environmental conditions.

Genetic Engineering and Synthetic Biology, Food Security and New Crops

More controversial than genomics in selection, genetic engineering and synthetic biology could transform future agriculture under conditions of grand challenges. There are many publications regarding risk associated with genetic modification, most of them indicating low risk (e.g. European Commission 2010). As the challenge in a future with many more mouths to feed, while climate effects may negatively interact with crop growth and yield, genetic modification may be the most sustainable approach. Here lies the potential to adapt crops to warmer and drier climates and to increase the net yield of harvests on less land, with less input of water and agrochemicals, so that the impact on biodiversity should be as low as possible.

Again it is not within the scope of this paper to be comprehensive. Given the need for more crops and higher yields with improved nutritional qualities, there are other serious problems that may be posed by grand challenges, e.g. new and migrating plant pathogens (such as the fungal banana diseases), multiple stresses (such as drought and heat already discussed), flooding, increased salination of soil. Further, new stresses are likely to arise more frequently, driving a need for faster approaches to crop development and adaptation. This is how a future synthetic biology could be very beneficial, if its 'design and engineering' expectations come to fruition. This would remove much of the trial-and-error from crop design, allowing targeted modifications in more rapid time frames.

Crops that make their own fertiliser

Several efforts are on-going in this tantalising research area. A collaborative project with UK and US scientists aims to design and build a synthetic biological module that could work inside a cell to perform the function of fixing nitrogen.[16] The cyanobacteria are able to fix nitrogen using solar energy via specialised cellular machinery. This project aims to re-engineer this machinery so that it can be transferred into a new host bacterial chassis as a first step towards transferring the machinery, and thus the ability to fix nitrogen, into plants themselves.

If successful, the significance of crops of the future that make use of atmospheric nitrogen rather than using synthetic fertilisers needs to be appreciated. The reliance of artificial nitrogen fertilisers for food crop production and their damaging environmental effects are often underestimated. For example, the Haber-Bosch process for the production of ammonia, which is used to produce agricultural fertilisers consumes 3 to 5 per cent of the world's natural gas production and releases large quantities of CO_2inthe atmosphere (Licht *et al.* 2014). Therefore, it may be possible to decouple agriculture from the fossil fuels industry.[17] Other effects of intensive fertiliser use, such as the concerns about nitrates in water and vegetables, and eutrophication of water bodies, have been recognised for decades (e.g. UN FAO 1972). Nevertheless, such a strategy is likely to meet with resistance from the public if the necessary safety research has not been conducted, and communicated, to minimise other environmental effects.

3.3 Sustainable Forestry

Major global economic models tentatively suggest that ambitious climate change mitigation need not drive up global food prices much if the extra land required for bioenergy production is accessible or if the feedstock, such as wood, does not directly compete for agricultural land (Lotze-Campen *et al.* 2014). What is not clear, however, is what will be the long-term effect on wood prices. Increasing demand for wood pellets is likely to drive up the price of biomass significantly in a market constrained by supply, not demand (Deloitte 2012). There is a danger in this that the demand for pellets overcomes the sustainable production of wood, and this could affect Asian countries directly through deforestation and its attendant problems, e.g. soil erosion.

A new approach to forest development and exploitation, particularly regarding the sustainability of new forestry, is also critical to second generation biofuels development (OECD 2013a). As well as the woody energy crops, some fast-growing tree species have also shown promise for biofuels production. Important attributes include the relatively high yield potential, wide geographical distribution, and relatively low levels of input needed when compared with annual crops (Smeets *et al.* 2007).

However, the lignin, a major component of plant secondary cell walls in woody plants, makes the sugar molecules that build the cellulose microfibrils less accessible to enzymatic depolymerisation and fermentation and thus limits the conversion of biomass to bioethanol. Down-regulation of one of the central genes in the lignin biosynthetic pathway in poplar trees produces wood that contains about 20 per cent less lignin and more cellulose per gram of wood. Lab and greenhouse experiment indicated that at least 50 per cent more bioethanol can be produced by this low-lignin wood. Results from field trials largely confirm these experiments although when the lignin level is too low there is a significant reduction of yield of wood (Van Acker *et al.* 2014).

The forest products sector is looking for new opportunities to produce value-added products while securing access to emerging carbon capture markets (Sheppard *et al.* 2011) and the example of lowering lignin content in wood may open new opportunities, especially as the approach although classified under GM is not using transgenic expression of poplar foreign genes.

Extending the limits of conventional breeding, which is a very slow and inefficient process in tree development, to give faster and more accurate trait improvement for application in plantation forests (including faster growth, improved pest and disease control) has the potential to allow easier and cheaper development of bioenergy and second generation biofuels.

3.4 Metabolic Engineering and Industrial Production

In a resource-constrained future world, bioenergy, biofuels and bio-based chemicals and plastics will use biomass as the feedstock, thus competing directly for land with food and feed. A clear interaction of energy security, food security and climate change is visible here.

Metabolic engineering of (primarily) microbial strains is increasingly being used to make both natural and synthetic organic chemicals. In mass production of the scale of bulk chemicals and transportation fuel, biotechnology processes have been notoriously inefficient, and unable to compete with the petrochemicals industry. The biocatalyst usually lacks the industrial robustness that is required to synthesise products at high yield under industrial conditions (Olson *et al.* 2012). Part of the vision for synthetic biology in the bio-based industries is to improve on these inefficiencies. Another part of that vision is to improve on greenhouse gas (GHG) emissions savings in bio-based production, which are already viewed as significant in comparison to the equivalent petrochemically manufactured products (e.g. Weiss *et al.* 2012).

The bio-based industries are placed in a position of competition for biomass and land in the production of food. Another frontier for synthetic biology in the future bioeconomy, then, will be applications that alleviate the strain on sustainable biomass production in the face of an increasing global population, when the primary focus must be on food (Pavanan *et al.* 2013). For example, fermentation of waste industrial gases takes pressure from land as the source of carbon for bio-based chemicals production (e.g. Bomgardner 2012).

Replacing the Oil Barrel

The arguments discussed regarding climate change and the need to leave large amounts of oil, gas and coal unburned has been a significant spur for R&D on liquid biofuels and bio-based chemicals and plastics. To be consistent with renewability, sustainable development and a future low-carbon society, a reality check relates to how much change in lifestyle society will tolerate. The Milken Institute (2013) estimated that 96 per cent of all manufactured goods in the US contain at least one chemical, and businesses dependent on the chemical industry account for nearly US$3.6 trillion in US GDP. The only feasible source of carbon to continue making chemicals is renewable, bio-based carbon.

To make the plethora of chemicals synthesised in the petrochemicals industry directly from metabolically engineered microbes is unrealistic. What is more realistic is to make bio-based intermediates, and use these as the basis for further production through (green) chemistry. It is estimated that over 30 different intermediate chemicals could be manufactured sustainably and economically from inexpensive sugar in the future (Burk 2010). Now it has been shown that entirely unnatural chemicals can be synthesised in metabolically engineered microbes (Yim *et al.* 2011). In the past few years much progress has been made in bio-based production of chemicals, and the idea of (eventually) replacing the oil barrel seems much less fanciful now than previously (Jiménez-Sánchez and Philp 2015).

4. Rice, the Iconic Crop of Asia

Rice is the major staple food for almost half of the world's population. Perhaps more than any other, rice is a defining crop of Asia. It has naturally been the model cereal for genetic, breeding and agronomic research. This is a fortuitous choice: rice has a small genome, it is easily transformed and there are similarities of its gene order and gene sequence with other cereals (Upadhyaya and Dennis 2010).

Conventional breeding over the last three decades has resulted in a doubling of rice production. However, breeders are in need of new tools and resources with which they can address the major production constraints such as pests, pathogens, submergence, salinity and drought in order to provide the required increase in the rate of production. Rice genomics has the potential to provide such tools and resources in the form of molecular markers for genes and gene control sequences determining the desired traits or as genes and gene control sequences *per se* for use in transformation breeding.

Regarding climate change and other abiotic threats to crop production, a major challenge is identifying genes involved in complex traits of agronomic significance. It is likely that there will be many genes with some effect in abiotic stress, and pinpointing critical genes will require inputs from all aspects of genetics and genomics. These characteristics will be of critical importance in altered environments caused by changing climate.

4.1 Rice and Submergence Tolerance

Rice is a crop well adapted to wet, monsoon climates and allows farmers to produce food in flooded landscapes. Of the lowland rain-fed rice farms worldwide, over 22 million hectares are vulnerable to flash flooding, representing 18 per cent of the global supply of rice. In total, some 30-40 million hectares get submerged, and this happens roughly every three years. Most rice varieties can tolerate only a few days of submergence and die after about a week.

Success in fine mapping of SUBMERGENCE 1 (SUB1), a robust quantitative trait locus (QTL) on chromosome 9 from the submergence tolerant FR13A landrace, has enabled marker-assisted breeding of high-yielding rice capable of enduring transient complete submergence (Bailey-Serres *et al.* 2010). It provides protection from complete submergence for 3-18 days. SUB1 belongs to the Ethylene Responsive Family (ERF) transcription factors (Xu *et al.* 2006). It functions by slowing down growth, preserving chlorophyll and conserving energy reserves.

With traditional lowland rice, when flooded the plant reacts by spurring growth to get above the water, continues to grow when the flooding continues, and finally runs out of nutrients and dies. Variety SUB1A does not grow while flooded and starts growing again after the flooding has subsided. In this case a single mutation is involved in tolerance.

SUB1 has been introduced into several mega-varieties of rice through marker assisted selection (MAS) and backcrossing[18] (MABC). Under submergence for 7-14 days these tolerant cultivars have an average yield advantage of 1.5 tonnes per hectare over intolerant cultivars, with no reduction in yield under non-submerged conditions. SUB1 is gradually being introduced to all varieties developed for lowland ecosystems by the International Rice Research Institute (IRRI)[19], and several national programmes are also introducing the gene into locally-adapted varieties. To date, over 4 million farmers have been reached with seeds of SUB1 varieties with the cooperation of the private sector.

Social Impacts

About 90 per cent of the world's rice is produced and consumed in Asia. Over 70 per cent of the world's poor are in Asia. In Asian countries with subsistence rice farming, when submergence occurs and the rice crop fails, the first most obvious effect is that the farmers' income decreases. Almost the first knock-on effect is that the farmers attempt to save money by taking their children out of school. They may be forced to sell land. Continuing poverty leads to people migrating off the land to find jobs in cities. So the cycle of poverty in the countryside continues.

One of the difficult issues encountered is to convince farmers to switch from their traditional varieties to the submergence resistant rice varieties. The strategy taken by IRRI was to convince single farmers to use the resistant varieties on one field, and when flooding happened the result of this is so convincing that most farmers around were convinced to switch. There is evidence that the introduction of submergence tolerant rice strains is now decreasing these negative social effects, and efforts are underway in the IRRI to try to quantify these effects.

4.2 Golden Rice

The story of Golden Rice is interesting beyond the science. It speaks to the geographical divisions on attitudes to GM technologies, and on their regulation. The story is concisely summarised by Potrykus (2013). Vitamin A deficiency is a serious health problem in rice-dependent populations, which are often poor. Genetic engineering provided a solution to produce beta-carotene in the endosperm of rice. Beta-carotene is then converted to vitamin A in the intestine. Only 40 grams of GM Golden Rice a day (modified for the production of vitamin A) are sufficient to prevent the severe health consequences of vitamin A deficiency. However, the deployment of this technology was delayed for 12 years by regulation. More recently, however, it seems that Golden Rice is gaining better acceptance.[20]

5. Banana: a Critical Food Security Crop with many Threats

> "*The* Musa *genome sequence is therefore an important advance towards securing food supplies from new generations of* Musa *crops…*" D'Hont *et al.* (2012).

5.1 Banana and Food Security

Banana as a crop for food security is often overlooked and yet it is the fourth most important food crop in the world. It is a staple in many diets. A large number of people in East Africa consume 1 kg or more per person per day. India and Uganda are the largest producers, but none are exported: the whole crop is required for food security. More than 70 million people in West and Central Africa are estimated to derive more than one-quarter of their food energy requirements from plantains. Banana is the most popular fruit in industrialised nations (Lescot 2011). But this is all from one variety

– Cavendish – and in global terms it is relatively minor. In 2012, the volume of global gross banana exports reached a record high of 16.5 million tonnes, but this represents only 15–20 per cent of total banana production.

Banana is perhaps the most important orphan crop of all. Because of the fact that banana reproduces mostly vegetatively, breeding and increasing the gene pool within a species is complicated.Crop species like this may benefit more readily from genetic modification arising from direct introduction of genes isolated from other species or organisms. The Musa Germplasm Information System (MGIS)[21,22] contains key information on *Musa*germplasm diversity, including: passport data; botanical classification;morpho-taxonomic descriptors; molecular studies; plant photographs, and; GIS information on 2281 accessions managed in 6 collections around the world. This is the most extensive source of information on banana genetic resources globally. However, information on the wild ancestors of the current banana varieties in Asia is still unknown. Having access to the full germplasm is important to address the pathogen attacks that many banana cultures are facing. This complete germplasm is likely to lead to new pathogen resistance genes.

5.2 Banana is Threatened by Many Pathogens

Various pathogens and pests threaten banana crops and its attendant food security (De Lapeyre de Bellaire *et al.* 2010; Dita *et al.* 2010). The race against pathogen evolution is particularly critical in clonally propagated crops such as banana. For example, *Fusarium* wilt, known as Panama disease, is a lethal infection caused by the fungus *Fusariumoxysporium*. Once infected,the plant is effectively doomed. *Fusarium* destroyed the Gros-Michel banana plantations in Central America in 1950s.

A new strain, Tropical Race 4 (TR 4), identified first in Malaysia, has spread to other South East Asian countries. It is now also in the Middle East and southern Africa. In Queensland, Australia, it threatens to make the AUD 600 million banana industry extinct.Tropical Race 4 attacks not only the Cavendish cultivar, but also many other cultivars grown widely in subsistence farming systems in Africa. What is worse, *Fusarium* spores can persist in soil for many years, so eradication of TR4 will require an approach similar to Ebola outbreaks – tracing all possible infection paths and quarantine.

Pest control is also expensive. Up to 50 pesticide treatments a year are required in large plantations against black leaf streak disease (also known as Black Sigatoka), a recent pandemic caused by *Mycosphaerellafijiensis*. The situation is not helped by monoculture: every Cavendish is genetically identical, and all have the same susceptibility to disease. Other major threats for banana include banana bunchy top virus (BBTV), burrowing nematode and banana weevil. More recently, banana *Xanthomonas* wilt (BXW) has emerged as an important bacterial disease that apparently originated in Ethiopia and caused a major disease epidemic in much of East Africa in the last decade. Breeding for resistance to these diseases and pests is one of the major goals in Africa and Asia.

The potential of natural resistance is very well illustrated in the banana variety Yangambi km5 (Hölscher *et al.* 2013). This variety is resistant to the nematode *Radopholus similis*, a roundworm that infects the root tissue of banana plants. This roundworm infects banana crops worldwide. The nematodes are invisible to the naked eye, but they can penetrate the roots of banana plants by the thousands. Once infected, these plants absorb less water and nutrients, resulting in yield losses of up to 75 per cent. Lesions in the roots also make the plant more susceptible to other diseases. Eventually, the roots begin to rot. In the final stage of the disease, the plant topples over, its fruit bunch inexorably lost. Analysis of Yangambi km5 indicated this variety produced nine metabolites that are toxic for nematodes. The popular Grande Naine is very susceptible to the nematode infection although it also produces these metabolites, be it much more slowly and in lesser quantities. These findings open new perspectives to use in plant protection.

5.3 The Banana Genome and Breeding

Very few new varieties have been obtained by crossing (e.g. FHIA-01 Goldfinger, FHIA-03 Sweetheart). A few new varieties have been obtained by mutational breeding (e.g. GCTCV-218 Formosana). But acceptance of the new varieties has been low because of different taste, ripening, cooking qualities. Among the difficulties are:

- Banana is seedless and most clones are also pollen sterile;
- It is very difficult to obtain seed from cultivars;
- It is very difficult to germinate viable seedlings;

- They are relatively large plants with long cycles;
- Inadequate germplasm collection, and vitally; and
- The understanding of the genetic mechanism of parthenocarpy[23] and unreduced gametogenesis is completely lacking.

The reference *Musa* genome sequence is considered a major advance in the quest to unravel its complex genetics. Having access to the entire *Musa* gene repertoire is a key to identifying genes responsible for important agronomic characters, such as fruit quality and pest resistance (D'Hont *et al.* 2012). In South East Asia, at its origin, wild *Musa* still remains, although the global gene pool information is still missing. Access to wild varieties could lead to identification of resistance markers that can be used against pest attacks through breeding or breed more nutritious hybrids.

6. Oil Palm: An Asian Crop at the Nexus of Bioeconomy Issues

Oil palm illustrates a classic bioeconomy dilemma. It is the most productive oil-bearing crop, accounting for one-third of all vegetable oil and 45 per cent of edible oil worldwide. Although it is planted on only 5 per cent of the total world vegetable oil acreage, increased cultivation competes with dwindling rainforest reserves. Global production of palm oil more than doubled between 2000 and 2012 (FAO 2013). Thus, the competing imperatives of a bioeconomy are clear to see: creating economic growth while reining in detrimental environmental effects to create a future economy that is sustainable.

Palm oil production is central to the economy of Malaysia, employing close to half a million people. Historical statistics indicate that Malaysian palm oil yields have typically appreciated over time, until 2009, when an unexpected break in the long-term national growth pattern occurred which has persisted to the present day. Explanations for the abrupt change are varied, which include a combination of adverse weather, ageing trees and plant disease (USDA Foreign Agriculture Service, 2012).

Data indicates that the vast majority of trees have already reached or passed through their peak yielding years. A small but growing problem is a lethal fungal disease. *Ganoderma* has the capacity to cause significant yield losses well before it has actually killed an oil palm, while its spores can spread to ever increasing areas of a plantation once it has been introduced. Therefore, very obvious targets for genomics applications would be increasing oil yield and disease resistance. With growing needs for edible and biofuel uses, increasing yield would reduce the rainforest footprint of oil palm.

6.1 The Oil Palm Genome and Oil Yield

The oil palm genome sequence was published by Singh *et al.* (2013a). The sequence enables the discovery of genes for important traits as well as alterations that restrict the use of clones in commercial plantings. The oil palm is largely undomesticated and is an ideal candidate for genomic-based tools to harness the potential of this remarkably productive crop. The authors claim that the dense representation of sequenced scaffolds on the genetic map will facilitate identification of genes responsible for important yield and quality traits.

The modern oil palm tree *Elaeis guineensis* has three fruit forms: *dura* (thick-shelled); *pisifera* (shell-less); and *tenera* (thin-shelled). The *tenera* palm yields far more oil than *dura*, and is the basis for commercial palm oil production in all of South East Asia. In 2013 a remarkable discovery was made. The *Shell* gene has proven extremely challenging to identify in oil palm, given the large genome, long generation times and difficulty of phenotyping in experimental populations. Singh *et al.* (2013b) identified the gene and determined its central role in controlling oil yield. Regulation of the *Shell* gene will enable breeders to boost palm oil yields by nearly one-third, excellent news for the industry, the rainforest and its champions worldwide, and bioeconomy policymakers.

Seed producers can now use the genetic marker for the *Shell* gene to distinguish the three fruit forms in the nursery long before they are field-planted. Currently, it can take six years to identify whether an oil palm plantlet is a high-yielding palm. Even with selective breeding, 10 to 15 per cent of plants are the low-yielding *dura* form due to uncontrollable wind and insect pollination, particularly in plantations without stringent quality control measures (Cold Spring Harbor Laboratory News 2013).

Accurate genotyping such as this has a critical implication for a bioeconomy. Enhanced oil yields will optimise and ultimately reduce the acreage devoted to oil palm plantations, providing an opportunity for conservation and restoration of dwindling rainforest reserves (Danielsen*et al.* 2009).

7. Forestry and Genomics

Despite many publications regarding the use of waste materials in a bioeconomy, wood is currently the most widely used resource as a feedstock, and this is likely to continue. It is used in energy, biofuels and bio-based materials applications. Long experience of the exploitation of timber has shown the dangers of over-exploitation. That is why sustainable forestry is critical to future bioeconomy plans.

Malaysia, like other South East Asian nations, has an economy highly dependent on wood. Figures vary, but one estimate is that 62.3 per centof Malaysia is forested. Of this 18.7 per cent is classified as primary forest, the most biodiverse and carbon-dense form of forest. However, between 1990 and 2010, Malaysia lost about 8.6 per cent of its forest cover. Forests are very diverse in Malaysia, covering the ecosystem spectrum from mountain forests to mangroves. About 4.2 million cubic metres of timber are harvested annually from the forest in Peninsular Malaysia. The timbers consist of about 900 different species. As with all tropical rainforest systems, the main threats are global warming, loss of biodiversity and deforestation.

As in most countries, Malaysian forest genomics research and development is at an immature stage. Much other genetic knowledge is required to unleash the potential of genomics. However, future work is likely to fall into one of two (inter-related) categories: conservation of forest genetic resources, and; sustainable utilisation of forest genetic resources.

The Forestry Research Institute Malaysia (FRIM)[24]is a leading institution in tropical forestry research. Regarding genomics, the early development of this area is divided into five topics:

1. Microsatellite marker;
2. Genetic diversity of timber species;
3. Optimum population size for conservation;
4. Effects of logging on plant species; and
5. Full genome sequence of *Shorealeprosula*, a very important timber species.

Many of the Malaysian timber types are of high value, and the business is susceptible to both fraud and over-exploitation of rare species. Timber tracking is, therefore, very important on the international stage, and DNA barcoding is rising in importance. DNA barcodes are also important in the authentication of the many Malaysian medicinal plants.

Another large country with a relatively large dependence on forestry in its economy is Canada. In Canada the area of forest affected by natural disturbances such as insect infestations, e.g. the mountain pine beetle, and wildfire is much larger than the total area of logging. These sources of biomass represent the largest potential for further development of the bioenergy industry in Canada by far. A strategic market is the EU, where biomass imports are predicted to triple between 2010 and 2020 (Lamers *et al.* 2014), with biomass demand to further increase up to 2030, mostly for bioenergy utilisation.

Recognised as a sector of economic importance in British Columbia, the forest sector has benefitted from significant investment from Genome Canada and Genome BC. Large sums have been invested in capacity-building discovery research along with a number of more applied research projects such as the:

- Development of genomic tools to identify forest fungi and understand forest ecosystems;
- Genomic resources for beetle-fungal-tree host interactions;
- Exploration of genome organisation and structure of spruce and pine trees;
- Understanding the genomic diversity of forests;
- Identification of genes activated during fungal infection;
- Developing tools to forecast mountain pine beetle outbreaks; and
- Testing of genomic markers for utility in management of climate change.

It is clear that these two countries, with very different forest resources, share similarities in their expectations from genomics research and the impact on forestry and the concomitant economic development.

8. Industrial Uses of Biomass with Reference to an Asian Bioeconomy

There is a large existing body of literature on the increasing number of crops and waste materials that can be used in bio-based production of fuels, electricity, plastics, chemicals and textiles. Indeed many of the crops being considered in OECD nations as non-food 'energy crops' have Asian or tropical origins. For example, the plant *Jatropha* is widely grown in tropical and sub-tropical regions for the oil.

Jatropha incentives in India are a part of the national goal to achieve energy independence (Biswas *et al.* 2014) and it is also grown in Africa as a promising alternative for biodiesel production.[25] For a long time, however, optimisation of production has long been neglected, while yields can be significantly improved in agronomy studies.[26] In addition, the right variety for the right environment needs to be selected. Breeding to develop cultivars that have high yield and result in a stacking of desirable traits are essential. Results from field trials in India demonstrated that yield can be significantly increased.

Arundo donax, the giant cane, is native to Eastern and Southern Asia, and is another promising crop for energy production (Lemons e Silva *et al.* 2015) in the Mediterranean climate of Europe and Africa that could benefit from selection breeding.

However, a detailed discussion is beyond the scope of this paper. Here, the discussion is limited to rice and banana and their potential for non-food uses. What is quite clear is that both of these crops are absolutely essential in food security for many people, especially in Asia and Africa. And in bioeconomy strategies food security is the top priority. However, in keeping with the ethos of the circular economy[27], it is paramount for society to start using waste materials as resources.In this regard, both rice and banana can also produce materials other than the edible components that can be used in a bioeconomy for industrial production.

Whereas all of the banana plant is in current use, and therefore, using it as biomass for industrial production may be seen as a competing use, a component of rice, the straw, currently represents a difficult waste disposal problem. More widely, it is important to realise that more than half of all absolutely dry matter in the global harvest is in cereal and legume straws;

in tops, stalks, leaves, and shoots of tuber, oil, sugar, and vegetable crops; and in pruning and litter of fruit and nut trees (Smil 1999). On the global scale, the non-edible part of crop production is a vast, untapped resource for utilisation in a bioeconomy.

8.1 Rice Straw: ADifficult Waste Product

Rice farming results in two types of residues – straw and husk – that are attractive in industrial use. Rice husk, the main by-product from rice milling, accounts for roughly 22 per cent of paddy weight, while rice straw to paddy ratio ranges from 1.0 to 4.3. Although the technology for rice husk utilisation is well-established worldwide, rice straw is sparingly used. One of the main reasons for the preferred use of husk is its easy procurement. In the case of rice straw, however, its collection is difficult and its availability is limited to harvest time.

Rice straw is unique relative to other cereal straws in being low in lignin and high in silica (Van Soest 2006). Silica (up to 12 per cent by weight, Nayar *et al.* 1977) and lignin in that order are the primary limiting factors in rice straw quality as an animal feed. As a result, widespread burning of rice straw at the field is practiced. The practice has been cited as an air pollution problem, with a possible link to increased instances of asthma (McCurdy *et al.* 1996; Torigoe *et al.* 2000).

The energy content of rice straw is around 14 MJ per kg at 10 per cent moisture content. The by-products are fly ash and bottom ash, which have an economic value and could be used in, e.g. cement and/or brick manufacturing. Straw fuels have proved to be extremely difficult to burn in most combustion furnaces due to engineering difficulties, especially those designed for power generation. Due to recent advances in lignocellulosic conversion, however, the possibility is opened up for the use of rice straw for bio-based chemicals production. There are at least 12 Asia-Pacific countries with biofuels mandates or targets (OECD 2014). Here is a unique opportunity. Rice is a huge volume crop, its straw, produced in very large volumes, is not only virtually of no use, its disposal by burning represents a health problem. Its use in bio-based production would, therefore, represent a new market opportunity for farmers that does not interfere with their other markets.

Two bio-based production strategies are worth noting. Kim *et al.* (2010) demonstrated that *Lactobacillus brevis* is able to simultaneously metabolise all fermentable carbohydrates in acid pre-processed rice straw hydrolysate for the production of high-value lactic acid. More controversially, Oraby *et al.* (2007) expressed the catalytic domain of the *Acidothermus cellulolyticus* endoglucanase gene in rice (to convert cellulose into fermentable sugars for subsequent fermentation to ethanol as biofuel). This is an alternative to using extracellular enzymes, which remain relatively expensive. They concluded that the approach may be commercially viable.

Expectations are rising in developing Asian countries like Indonesia for poverty alleviation and energy diversification through second generation biofuel production from rice straw.A recent (Samuel 2013) environmental and socio-economic assessment of rice straw conversion to ethanol for Bali, Indonesia was conducted. The study found that, assuming all the technically available rice straw in Bali is used (~244-415 kilotonne/year), ethanol production may yield: gasoline replacement, lifecycle GHG savings, GDP contribution, foreign exchange savings, and employment beneficiaries of: 55-93 million litres/year, US$ 140-240 million/year, 19-32 kilotonne of CO_2-equivalent/year, 100-180 million US$/year, and 2,200-3,700 persons, respectively.

8.2 Banana Waste Utilisation

Much of the banana plant, beyond the edible fruit, can be used for a variety of purposes. However, once the banana fruit is harvested in South China, Li *et al.* (2010) reported that the pseudostems become organic waste and cause environmental pollution.Cellulosic fibre obtained from the pseudostem of the banana plant is extensively used for paper board, tissue paper, clothing, weaving baskets and natural sorbents (Mohapatra *et al.* 2010). However, banana sap from the pseudostem is under-utilised. Paul *et al.* (2013) investigated the productionof a bio-based resin from the pseudostem banana sap. They discussed the possible use of such a resin in the automotive industry.

8.3 Justification for the Dual Use or Cascading Use of Vital Food Crops

By focusing on two critical Asian crops, it is hoped that it can be demonstrated that even food crops that are considered top priority can find a role in bio-based production of industrial materials such as fuels and chemicals without interfering with their primary role in food security. Governments can invest in the R&D required to explore the possibilities for such utilisation at relatively low cost. Many such investigations will prove fruitful in research but will not prove to be commercially viable. But when a commercially viable proposition is discovered, the advantages could include:

- Above all, extra markets are offered to farmers for their produce that may help them escape poverty, or at least improve income security;
- Achieving sustainability in a bioeconomy, and helping to meet national emissions reduction targets; and
- In the case of rice straw, a serious air pollutant that causes environmental and human health damage could be removed.

When it is realised that in terms of total biomass produced, these by-products of agriculture account for more biomass than the food portion of the crop, this is the vast unexplored resource for use in a bioeconomy. Then a future role of government could be to incentivise collection and make sure that a robust infrastructure is established with the cooperation of the private sector.

9. Other Genomics-Related Topics Relating to Food Security in an Asian Bioeconomy

Along with increasing incomes in developing economies, there has been a large increase in meat and milk consumption. From the beginning of the 1970s to the mid-1990s, consumption of meat in developing countries almost tripled the increase in developed countries (Delgado 2003).

Taiwan offers a good example of this shift in dietary pattern as development proceeds. In the 30 years from 1959-1989, *per capita* consumption of rice halved, while meat consumption (chicken, beef and pork) quadrupled, fruit consumption quintupled, and fish consumption doubled (Huang and Bouis 1996). Similar patterns were seen in Japan and Korea as household incomes increased.

Growing animal protein foods requires large amounts of high-energy feed, water and land. Naturally, this creates strain on a bioeconomy as less biomass can be devoted to industrial uses. Therefore, there is clearly a need to find new ways for increasing food production efficiency. The roles of genomics can be subtle, but small incremental advances in selective breeding over many years can lead to significant effects. The major role of genomics could be to increase the speed and efficiency of traditional breeding. By selecting genes already in the food chain and their introduction to new varieties via breeding, this may overcome political GM issues.

9.1 Chicken as a Food Source in a Bioeconomy

Chicken is a major source of protein in the world, with around 20 billion birds alive today, producing around 1.2 trillion eggs.[28] Asia already consumes 40 per cent of global chicken production and consumption is growing.[29] It is the first livestock species to be sequenced and so leads the way for others (Burt 2005). It is an excellent food source in bioeconomy terms as its production is relatively low in GHG emissions (Table 1), and is cheaper to produce and less energy intensive than rearing lamb, beef or pork.

In parallel with the chicken genome sequencing project (Hillier *et al.* 2004), a consortium set about identifying single nucleotide polymorphisms (SNPs[30]). When a large number of these are verified, the availability of a standard set of 10,000 or more SNPs holds much promise towards the identification of genes controlling quantitative trait loci (QTL), including those of economic interest.

One of the key traits improved every year through selective breeding is feed efficiency – the number of kilos of animal feed needed to produce a kilo of poultry meat (Technology Strategy Board 2010). Genomic technologies are expected to enhance this trend. Since animal breeding is cumulative, even small enhancements to the rate of improvement can multiply into huge differences for commercial customers over time and have very large impacts. The result of this is that more people can be fed from the same land resources or land resource can be freed up – for example for biomass production for industrial use.

The Aviagen[31] genomics project, for example, is concerned with identifying naturally occurring markers within the genome of elite birds and using those markers to help breed stronger and more productive birds through the current selective breeding programme, a completely natural process. Aviagen became the first company to include genomic information as a critical additional source of information in a R&D breeding programme.

Table 1: The GHG Emissions Associated with Various Meat Production Systems

Product	CO_2 (eq kg^{-1})	Comments
Beef	44.8	Mainly a result of methane and N_2O, not CO_2
Belgian beef	14.5	
Idaho and Nebraska beef (average)	33.50	Farm-gate, quoted as 15.23 kg per pound of beef
Idaho lamb	44.96	Farm-gate, average of low and high productivity
Swedish pork	3.3-4.4	
Michigan pork	10.16	Farm-gate
Farmed trout	4.5	Raised in ponds. Frozen, leaving retailer
Cod	3.2	Frozen fillet, leaving retailer
Chicken	2.0	(Round weight, US)
Poultry (US)	1.4	
Chicken	4.6	(Round weight, UK)
Farmed salmon (sea-based, UK)	3.6	Including processing and transportation
Farmed salmon (sea-based, Canada)	4.2	Adjusted to fillet based on figures for live fish
Farmed salmon (sea-based, Norway)	3.0	Transportation to Paris
Farmed salmon (global average)	2.15	Farm-gate estimates
Capture fish (global average)	1.7	

Source: OECD (2013b).

9.2 Beef Production

The Australian beef industry today sees "*unprecedented demand from the entire Asia Pacific as well as the Middle East*" (Kondo 2014), whereas before the demand was mostly from Japan, and then later China. But beef production requires lots of land, feed, water and creates large GHG emissions, therefore, measures that improve beef production efficiency are being sought. Genomics offers some solutions.

The possibility of predicting breeding values using genomic information has revolutionised the dairy cattle industry and is now being implemented in beef cattle. A challenge in the development of genomic tools for beef cattle selection, however, is in the diversity of breeds represented in the industry.

There is large scope for the development of novel applications in the livestock sector, such as selection tools for new traits (meat quality, diseases resistance, feed efficiency, heat tolerance), animal traceability and parentage verification (e.g. McClure *et al.* 2013). Efforts in sequencing important animals in the global beef industry are underway to identify variants and to associate those variants with the genetic variation observed across beef populations.

It is also feasible to postulate that in the near future the artificial reproductive technologies (ART), such as artificial insemination, embryo transfer and in-vitro fertilisation, combined with genomic evaluation (GE) approaches will be the driving forces to lead cattle breeding to a finer process than it is nowadays.

9.3 Genomics and the Fishing Industry

Between 1998 and 2008, global exports of fish products doubled to a value of over US$100 billion. It is estimated that over 20,000 species of fish are used for food. Of a total global fishers (i.e. excluding aquaculture) of over 34 million in 2008, over 8.25 million were in China alone, and over 2.25 million in Indonesia (compare this to just under 13,000 in Norway). From the bioeconomy perspective, fish protein relieves pressure on land as the source of biomass for both agricultural and industrial uses. Given the health benefits and the lower GHG emissions associated with fish (Table 1), increased fish consumption would appear to be desirable for a future bioeconomy.

However, about 90 per cent of global wild fish stocks are already at capacity or are in precipitous decline.[32] Wild fisheries should, therefore, be regarded as 'not necessarily renewable'. Well-reported universal difficulties associated with wild fisheries are related to fish species identifications, e.g. species with limited diagnostic morphological features, cryptic species, juvenile identification, or unavailability of adequate drawings and descriptions. Such problems are probably global, with almost 34 per centof the world's fisheries catch from 1950–2002 lacking species level identification.

Molecular markers, such as DNA barcodes, can address many such difficulties. In addition to the use of DNA barcodes for species delimitation, the availability of a standardised and globally accessible database (Barcode of Life Data System, BOLD)[33],facilitates numerous related applications, including issues relating to traceability, illegal fishing and fish fraud (Costa *et al.* 2012). A common fraudulent practice is species substitution, which can be unintentional or intentional for tax evasion, for laundering illegally caught fish or for selling one fish species for a higher-priced species. Traceability is become an increasing urgent need.

For example, about 70 per cent of the global tuna fish catch is taken from the Pacific. Most of the 23 tuna stocks are either over-exploited or depleted. Bluefin tuna are unrivalled in popularity, especially in sushi, and the economic value per fish is unmatched by any other species. However, its over-exploitation seriously threatens its future, and some advocate that consumers should avoid eating bluefin altogether. Moreover, prices of yellowfin tuna and Pacific bluefin tuna are drastically different. But if they are used in cooking, it is difficult even for experts to distinguish between them. DNA barcoding,therefore,holds out promise for various policy goals: to reduce fraud, to play a role in cultivating conscientious consumerism (by helping threatened species conservation) and to effectively regulate by eliminating market ambiguity (Lowenstein *et al.* 2009).

To date, no one technique is perfect in its ability to identify species at the molecular level. However, DNA barcoding analysis is a significant advancement upon previous DNA techniques because it is based on a universal methodology (Hanner *et al.* 2011). It has been argued that linking DNA barcoding to a universally accessible, expert-authenticated database of species identification data would address many of the problems that plague the current system of species authentication (Clark 2015).

9.4 Aquaculture and Genomics

Aquaculture production has continued to grow annually at around 6-8 per cent. Today, farmed seafood production exceeds that of wild fisheries and has significant potential for future growth. World aquaculture is heavily dominated by the Asia–Pacific region, which accounts for roughly 90 per cent of production, mainly due to China. In 2008, 85.5 per cent of fishers and fish farmers were in Asia, compared to 1.4 per cent in Europe and 0.7 per cent in North America (FAO/WHO 2010). However, much remains to be done in productivity in Asia: fish farmers' average annual production in Norway is 172 tonnes per person, while in China it is 6 tonnes and in India only 2 tonnes.

High priority traits for farmed fish are the development of single sex populations and improving disease resistance. Production of mono-sex female stocks is desirable in most commercial production since females grow faster and mature later than males. Understanding the sex determination mechanism and developing sex-associated markers will shorten the time for the development of mono-sex female production, thus decreasing the costs of farming.

Nile *Tilapia* is one of the most important farmed species with a production exceeding 2.8 million metric tonnes in 2010. *Tilapia* farming is increasingly important in Asia, with (at least) Bangladesh, China, Indonesia, Malaysia, Myanmar, the Philippines, Thailand and Vietnam all producing significant tonnages. Most Asian countries do not export significant amounts of *Tilapia*, demonstrating its role in food security.

Tilapia is unusual in that intensive commercial production generally requires all-male stocks, not only because males grow faster but also to avoid uncontrolled reproduction before harvest. A restriction associated DNA (RAD) sequencing study by Palaiokostas *et al.* (2013) identified a reduced candidate region for the sex-determining gene(s) and a set of tightly sex-linked SNP markers. Although they could not identify the causative gene(s), no female was mis-assigned using their sex-associated SNPs. This means that those SNPs could be of high practical value towards the production of all male stocks for the *Tilapia* aquaculture industry.

10. Concluding Remarks

The presence of an abundance of biomass in many Asian nations and a massive burden of crude oil importation makes Asia a continent where a bioeconomy should be exceptionally attractive. Moreover, climate change mitigation policy could prove very expensive for Asia, but the bioeconomy offers many new economic as well as environmental and social opportunities. It is impossible to predict all of these. This paper serves to highlight some of the major challenges and opportunities for Asia, utilising its traditional strengths in biomass production when allied to modern biotechnology and genomics.

However, bio-based production processes are notoriously inefficient. And although great strides have been made in agricultural efficiencies through traditional breeding techniques, -omics technologies open up the possibilities of making breeding much more quantitative and rapid. A few Asian countries are at the cutting edge of biotechnology and genomics. In other Asian countries, which have traditionally relied more heavily on exporting their natural resources, investments in growing biotechnology research infrastructure and encouraging both domestic and foreign private investments could be transformative. Their arrival within the status of 'developed' nations would also herald a knowledge-based economy that is entirely consistent with a new type of economy in which environmental protection is accorded a much higher importance because it make more economic sense – this is the essence of a future bioeconomy.

The paper is deliberately skewed towards food genomics for a very good reason. We previously outlined some of the challenges in bio-based production in an Asian bioeconomy (Philp and Pavanan 2013). Here we emphasise that these industrial production opportunities must be reconciled with food needs. What we hope we have shown is that biotechnology and genomics technologies can improve food and industrial production, with or without genetic modification, often in ways that are not obvious, and that the potential is only just beginning to be realised.

Fewer people than ever before are hungry, but switching to bio-based materials production obviously puts enormous strain on biomass availability. While the use of food crops for industrial production should by no means be discounted, we must also get much better at using waste materials of agriculture, forestry, food and industrial production as the feedstocks of the future. The -omics technologies and synthetic biology, converging with green chemistry, are the enabling technologies for that revolution.

Endnotes

1 Professor of International Child Health and Director of the UCL Institute for Global Health. See, https://www.ucl.ac.uk/intercultural-interaction/For_2website_Grand_Challenge_review_event_report.pdf

2 http://thediplomat.com/2013/02/japans-demographic-disaster/

3 Defined as all those living in households with daily per capita incomes of between USD10 and USD100 in PPP terms (OECD 2010).

4 http://www.fao.org/fileadmin/templates/wsfs/docs/expert_paper/How_to_Feed_the_World_in_2050.pdf

5 http://esa.un.org/wpp/Documentation/pdf/WPP2012_Volume-II-Demographic-Profiles.pdf

6 www.eia.gov/countries/cab.cfm?fips=JA

7 http://unfccc.int/meetings/copenhagen_dec_2009/items/5262.php

8 http://www.oxfordresearchgroup.org.uk/publications briefing_papers_and_reports/climate_change_drivers_insecurity_and_global_south

9 http://www.epa.gov/climatechange/impacts-adaptation/international.html

10 http://www.bbc.com/news/business-33119960

11 http://www.bbc.com/news/world-latin-america-30962813. January 24, 2015

12 http://www.unccd.int/en/regional-access/Asia/Pages/alltext.aspx

13 Food and Agriculture Organisation (FAO), www.fao.org/sd/epdirect/epre0045.htm

14 Marker assisted selection or marker aided selection (MAS) is a process whereby a marker (morphological, biochemical or one based on DNA/RNA variation) is used for indirect selection of a genetic determinant or determinants of a trait of interest (e.g. productivity, disease resistance, abiotic stress tolerance, and quality).

15 C3 refers to the Calvin cycle that plants use for photosynthesis. The C4 pathway is an alternative of the Calvin cycle. The latter pathway has an advantage because it fixes more carbon dioxide and can operate under low carbon dioxide concentrations, without inhibitory effects of oxygen or sunlight as is the case for C3 photosynthesis.

16 http://www.bbsrc.ac.uk/news/food-security/2013/130822-pr-uk-usa-collaborate-to-design-crops.aspx

17 When the price of Brent crude oil rose from around US$ 50 per barrel to about US$ 110 by January 2013, the prices for ammonia in western Europe and the mid-western corn belt in the United States roughly tripled.

18 Backcrossing is a crossing of a hybrid with one of its parents or an individual genetically similar to its parent, in order to achieve offspring with a genetic identity which is closer to that of the parent.

19 www.irri.org

20 http://www.goldenrice.org/

21 http://www.crop-diversity.org/mgis/

22 https://www.bioversityinternational.org/research-portfolio/conservation-use-of-bananas-tree-crops/international-musa-germplasm-transit-centre/

23 In botany and horticulture, parthenocarpy (literally meaning virgin fruit) is the natural or artificially induced production of fruit without fertilisation of ovules. The fruit is, therefore, seedless.

24 www.frim.gov.my

[25] https://www.cde.unibe.ch/News%20Files/BIA_policy_brief_jatropha_grows.pdf

[26] http://www.jatropha.pro/PDF%20bestanden/Quinvita%20presentation%20June%202011.pdf

[27] http://ec.europa.eu/environment/circular-economy/

[28] http://www.bbsrc.ac.uk/news/food-security/2013/130404-f-what-lives-inside-a-chicken.aspx

[29] http://www.thepoultrysite.com/articles/2929/global-poultry-trends-2013-asia-consumes-40-per-cent-of-worlds-chicken/

[30] A SNP represents a difference in a single DNA building block, called a nucleotide. http://ghr.nlm.nih.gov/handbook/genomicresearch/snp

[31] http://en.aviagen.com/research-development/

[32] http://www.bbc.com/news/business-33068446

33 www.barcodinglife.org

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