CHAPTER 11

Genomics and the Bioeconomy: Opportunities to Meet Global Challenges

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INTRODUCTION

In the wake of the worst financial crisis in living memory, a new, sustainable economy must be created. This coincides with a time in our history when there are grand challenges such as climate change and energy security to be faced. By 2050 it is expected that there will be at least 9 billion people alive: food and water security are also increasingly important politically. Soil is being destroyed at unsafe rates. For most countries waste disposal is becoming increasingly difficult as suitable sites for properly engineered landfilling are becoming scarce.

Building a bioeconomy in which the relationship between economic growth and increasing greenhouse gas (GHG) emissions is decoupled is one way to start to tackle these challenges. Since the OECD published a policy agenda for a bioeconomy [1], interest has been growing. In 2012 the United States published its bioeconomy blueprint, and the European Union launched its bioeconomy strategy. Several nations have developed their own bioeconomy strategies, for example, Belgium, Denmark, Finland, Germany, Malaysia, the Netherlands, and South Africa. Several other countries, although lacking a formal bioeconomy strategy, have important policies consistent with the bioeconomy concept, for example, France, Italy, Japan, Korea, and the UK [2].

At roughly the same point in history, genome sequencing has been transformed into a readily available technology as the cost has plummeted. The grant scheme run by the US National Human Genome Research Institute, officially called the Advanced Sequencing Technology awards, is known more widely as the “$1000 dollar genome” program as it predicted that the cost of sequencing a human genome could be reduced to this cost. Started in 2004, the scheme has awarded grants to 97 groups of academic and industrial scientists to a value of some $230 million, including some at every major sequencing company [3].

This has demonstrated to policymakers and others that biotechnology is a foundation for economic growth, something that has been disputed for decades. The economic impact already being experienced from the Human Genome Project (HGP) has far-reaching consequences. The $3.8 billion investment of the HGP not only launched the genomics and DNA sequencing revolution but has also driven close to a trillion dollars in economic impact and generated over 300,000 jobs in the US.
economy [4]. It is estimated that the return on investment has been $178 for every public dollar [5].

In the present context, we hope to highlight early progress on genomics and associated -omics technologies in several of the key sectors that a bioeconomy will rely on. It is clear that there is much capacity for improvement as the age of practical application of genomics to societal problems other than human health is in its infancy. Because a bioeconomy will need to reconcile the needs of industry and agriculture, this chapter has a focus in applications of genomics in these areas.

THE GRAND CHALLENGES ECOSYSTEM

Certain grand challenges are either here or are approaching. It is argued that they are particularly challenging as policies to tackle one of them will have effects on one or more of the others, not always in a positive manner. For example, growing more crops on more land, or increasing the productivity of crops on the existing land addresses food security. This strategy is likely to negatively affect soil health, and will require more water, which is already stressed in many locations. It may also decrease biodiversity. Higher yields will require more artificial fertilizers, which mean more emissions and agriculture becoming even more dependent on the fossil industry. More agrochemicals can lead to further pollution. Bioenergy, biofuels, and bio-based materials produced from biomass instead of fossil resources address 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 other ways.

Energy security

Most countries are plagued by energy insecurity. Nearly all European countries are net importers of oil and gas. India imports 80% of its domestic crude oil requirements [6]. The cost of crude oil imports account for more than 10% of the GDP of Thailand [7]. The United Kingdom became a significant net exporter of crude oil beginning in the early 1980s, but has been a net importer since 2005.¹

No country illustrates the situation better than Japan, the world’s third largest economy which is just 16% energy self-sufficient.² 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% 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

¹ http://www.eia.gov/todayinenergy/detail.cfm?id=16971
² www.eia.gov/countries/cab.cfm?fips=JA
gas demand. Japan consumed an estimated 4.5 million barrels per day of oil in 2011, while it produced only about only 5000 barrels per day [8].

Meanwhile the stakes are rising. New oil discoveries globally have not kept up with annual consumption since at least 1980. Currently some specialist oil companies have high percentages of their potential capex over the next decade in high-cost, high-risk projects, especially deep water or oil sands, which may require a $95 per barrel price [9]. Currently almost a third of the oil consumed in the world comes from underwater reservoirs. And as offshore oil exploitation is moving into increasingly deep waters, the risks of accidents increases—for an average platform, each 30 m of added depth increases the incident probability by 8.5% [10].

**Climate change**

There is now overwhelming scientific consensus on the existence of anthropogenic global warming [11]. Over 80% of global emissions are caused by countries that have participated in the Copenhagen Accord, which recognizes a need to limit the temperature rise though global warming to 2°C. And yet, the world seems on a trajectory consistent with a long-term average temperature increase, which is significantly higher [12]. Therefore most of the known and projected fossil fuel reserves may be unburnable [13]. This conclusion has been contested by key companies in the oil industry [14], although there is a gradual realization in the industry that climate change will affect how it does business [15].

McGlade and Ekins [16] have calculated that a third of oil reserves, half of gas reserves, and over 80% of current coal reserves should remain unused from 2010 to 2050 in order to meet the 2°C obligation. Critical work on climate change came from the Intergovernmental Panel on Climate Change (IPCC) during 2014. In April 2014, the Working Group III contribution to the IPCC’s Fifth Assessment Report Scenarios [17] showed that, to have a likely chance of limiting the increase in global mean temperature to 2°C, means lowering global GHG emissions to near-zero by the end of this century.

**Food and water security**

With 9.1—9.6 billion alive by 2050 as estimated in the medium variant option, food production will need to rise by 50—70% [18]. 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. The mantra will become “more from less.”

4 www.ipcc.ch
As many as 2 billion people rely directly on aquifers for drinking water, and 40% of the food in the world is produced by irrigated agriculture that relies largely on groundwater. Globally, 70% of all freshwater use is for agriculture [19]. Vast territories of Asia rely on groundwater for 50–100% of the total drinking water [20] and groundwater depletion is accelerating worldwide. Some of the highest rates of depletion are in some of the world’s major agricultural centers, including northwest India, northeast China, and northeast Pakistan [21]. Sophisticated modeling has suggested an 80% likelihood that at least one decades-long mega-drought will hit the Southwest and Midwest United States between 2050 and 2100 [22].

**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% of all food is derived from cropland [23]. But soil is being destroyed at unprecedented rates due to soil erosion (e.g., through deforestation), pollution, and salination. About 2.5% of arable land in China is too contaminated for agricultural use [24].

It takes around 500 years to form 25 mm of soil under agricultural conditions, and about 1000 years to form the same amount in forest habitats. Therefore soil should be treated as a nonrenewable resource. In the bioeconomy and sustainability context, soil accounts for some 20% of the capture of human CO₂ emissions [25].

**FOOD PRODUCTION IN A BIOECONOMY**

A primary focus of a bioeconomy is to reduce GHG emissions. That is a primary driver behind the bio-based industries replacing fossil resources exploitation to make fuels and materials. Agriculture is also enormously important in climate change mitigation strategies. Table 11.1 provides in broad terms the GHG emissions associated with the production of major protein sources. Although the sources of information use different methodologies, the table highlights that there are large differences, and that ruminant production is much worse in GHG emissions terms that chicken and fish. However, with the growth of the global middle class [26], demand for meat has increased tremendously.

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 has been implicated in deforestation. For every kilogram of beef produced, 4–5 kg of high energy feed are required, and well over 10,000 l of water is consumed.

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5 Food and Agriculture Organization (FAO), www.fao.org/sd/epdirect/epre0045.htm
What has genomics to offer? It is impossible to answer the question exhaustively in this chapter; rather a flavor of how genomics can influence food production is given. Moreover, the vast majority of applications of genomics to food and feed production have yet to be thought of. Nevertheless, at this early stage, it is quite clear that there are significant advances in the efficiency of food production to be made, even without genetic modification. Currently it is the alliance of genomics technologies with modern and conventional breeding technologies that is making greatest strides.

### Beef production

Given the popularity of beef, genomics has started to be used to increase the efficiency of production, for example, to enhance meat quality during breeding or rearing. One of the greatest challenges to successful application of genomics, however, is

<table>
<thead>
<tr>
<th>Product</th>
<th>CO₂ (eq/kg)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beef</td>
<td>44.8</td>
<td>Mainly a result of methane and N₂O, not CO₂</td>
</tr>
<tr>
<td>Belgian beef</td>
<td>14.5</td>
<td></td>
</tr>
<tr>
<td>Idaho and Nebraska beef (average)</td>
<td>33.50</td>
<td>Farm-gate, quoted as 15.23 kg per pound of beef</td>
</tr>
<tr>
<td>Idaho lamb</td>
<td>44.96</td>
<td>Farm-gate, average of low and high productivity</td>
</tr>
<tr>
<td>Swedish pork</td>
<td>3.3–4.4</td>
<td></td>
</tr>
<tr>
<td>Michigan pork</td>
<td>10.16</td>
<td>Farm-gate</td>
</tr>
<tr>
<td>Farmed trout</td>
<td>4.5</td>
<td>Raised in ponds. Frozen, leaving retailer</td>
</tr>
<tr>
<td>Cod</td>
<td>3.2</td>
<td>Frozen fillet, leaving retailer</td>
</tr>
<tr>
<td>Chicken</td>
<td>2.0</td>
<td>(Round weight, United States)</td>
</tr>
<tr>
<td>Poultry (United States)</td>
<td>1.4</td>
<td>(Round weight, United Kingdom)</td>
</tr>
<tr>
<td>Chicken</td>
<td>4.6</td>
<td>Including processing and transportation</td>
</tr>
<tr>
<td>Farmed salmon (sea-based, United Kingdom)</td>
<td>3.6</td>
<td></td>
</tr>
<tr>
<td>Farmed salmon (sea-based, Canada)</td>
<td>4.2</td>
<td>Adjusted to fillet based on figures for live fish</td>
</tr>
<tr>
<td>Farmed salmon (sea-based, Norway)</td>
<td>3.0</td>
<td>Transportation to Paris</td>
</tr>
<tr>
<td>Farmed salmon (global average)</td>
<td>2.15</td>
<td>Farm-gate estimates</td>
</tr>
<tr>
<td>Capture fish (global average)</td>
<td>1.7</td>
<td></td>
</tr>
</tbody>
</table>

Source: Adapted from Ref. [27–29].
the wide diversity of breeds used across the industry. Cattle functional genomics is in its infancy. Some approaches to beef cattle genomics are given.

Some economically relevant traits, such as early life growth traits, are easily measured in the field. Many of which are not easily measured are key to production efficiency factors, such as animal health and feed efficiency [30]. Partly this is the problem of the impracticality and/or cost of collecting field data, but the variety of breeds adds to the difficulties. To address this, sequencing efforts of important animals in the global beef industry are being made to identify variants and to associate those variants with the genetic variation observed across beef populations. In this way genomic selection tools may aid breeding programs.

Proven sire identification in breeding programs is extremely valuable, but parentage verification is a well-described problem, and is made more difficult by the large number of breeds. For example, McClure [31] employed microsatellite (MS) and single nucleotide polymorphism (SNP) from 39 breeds from Bos taurus and Bos indicus. An objective of this study was to develop a global SNP-MS reference panel that is inexpensive, easy to use, and can be used across the majority of these breeds.

When genomic approaches can routinely be combined with Artificial Reproductive Technologies, this will enable verification of the inheritance of favorable traits in in vitro embryos. This could make the whole selection and breeding process quicker and much more accurate [32].

Milk production
Genomics studies of milk have varied goals, underlining the significance of milk as a human food. Topics include the capacity of milk to manipulate the gut microbiota; manipulation of bovine milk fat; genetic selection for economically important traits, such as protein content; and diagnostics.

A very important economic trait is protein content, and in cattle the trait has a linkage to heritability. The application of genomics to breeding programs to improve protein yields would have obvious economic and societal benefits. For example, Raven et al. [33] produced evidence supporting a role for the RNASE5 (angiogenin ribonuclease, RNase A family 5) pathway in milk protein content, indicating that sequence polymorphisms associated with the genes involved explain some of the observed protein content differences. Their methodology contributes to the fundamental science of lactation, with practical implications for milk production with higher protein content.

Of particular relevance to milk is microbial spoilage [34]. Raw milk can harbor a variety of human pathogens and has been associated with serious foodborne illnesses such as diphtheria and brucellosis. Other, nonpathogenic species can produce
off-flavors, unwanted acidification, and thereby can contribute to lower shelf life. With a rise in consumption of raw milk, the risks are obviously greater, but pasteurized milk is not completely risk-free. The indigenous strains found in the dairy vary significantly from type strains, thus necessitating genome sequencing of additional dairy isolates to better understand how they survive in milk, and to subsequently take measures to ensure their eradication from it.

**Chicken as a bioeconomy food source**

Chicken is a major source of protein in the world, with around 20 billion birds alive today, producing around 1.2 trillion eggs. It was the first livestock species to be sequenced and so has led the way for others [35]. In parallel with the chicken genome sequencing project [36], a consortium set about identifying SNPs. When a large number of these are verified, the availability of a standard set of 10,000 or more SNPs holds much promise toward the identification of genes controlling quantitative trait loci (QTLs), including those of economic interest.

One of the key traits improved every year through selective breeding is feed efficiency (Figure 11.1)—the number of kilograms of animal feed needed to produce a kilogram of poultry meat [37]. 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.

![Figure 11.1](image)

**Figure 11.1** Chicken feed efficiency as a result of genetic improvement through breeding. (a) Feed conversion ratio over 20 years in meat-producing broilers at 42 days. (b) Broiler feed to produce a 2.5 kg chicken at 42 days. *Courtesy of Ref. [38].*

and have very large impacts. The result of this is that more people can be fed from the same land resources.

The Aviagen\(^7\) genomics project 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 program, 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 program.

**Crop production**

Feeding 9 billion people by 2050 is a major food security issue. Moreover, the demand for biomass for bio-based production of fuels, chemicals, and plastics will further stress land availability and productivity. The effects of climate change will exacerbate the difficulties facing conventional agriculture.

There are many applications of genomics to crop production that will be utilized in the future bioeconomy: pest resistance; more “efficient” plants that use less water; resistance to environmental stresses; and the development of crops that can fix nitrogen to replace synthetic fertilizers.

**Heat and drought stress: an increasingly important problem**

The 1988 drought in the Midwestern United States resulted in a 30% reduction in US corn production and cost about $39 billion [39]. The United States has just experienced its most widespread drought in more than half a century [40], and the drought in 2014 in California was perhaps the worst ever recorded [41]. Agriculture accounts for around 70% of all water use. Therefore measures that conserve water in agricultural use are of the utmost social and economic importance.

Drought is by far the most significant environmental stress in agriculture worldwide and improving yield under drought is a major goal of plant breeding. Despite much work on crop breeding for drought tolerance, there is still a large gap between yields in optimal and stress conditions. The complexity of drought tolerance mechanisms explains the slow progress in yield improvement.

Breeders now have much more genomics-related information available as new tools for breeding, such as markers for QTLs and single genes for plant transformation. Routine cloning of the genes underlying the QTLs is still a way off, but it will ultimately provide simple markers for an effective marker-assisted selection (MAS). Nevertheless MAS for drought tolerance will not be an easy task because dozens of QTLs for drought-related traits have been identified [42]. For many crop plants

\(^7\) [http://en.aviagen.com/research-development/]
information on drought-related QTL findings have been collected in open source databases, such as GRAMENE\(^8\) or GRAINGENES.\(^9\)

Major food crops are targeted for genomics investigations into drought tolerance, for example, wheat and barley [43]. Whole genome re-sequencing of maize (corn) is being used to identify drought tolerance genes [44]. Literature mining of the tomato genome by Bolger et al. [45] and filtering against drought- or salt-related QTLs has resulted in the identification of 100 candidate genes. Potato is the fourth most important crop in the world. Potato yield losses due to climate change are expected to range between 18% and 32% up to 2030. Many more drought response genes have been identified in wheat, rice, and maize than in potato. The identification of genes controlling drought responses in potato only started in 2007, and some (limited) progress has been made over the last few years [46].

With the rise of cultivation of nonfood crops specifically for energy purposes (to reduce competition with food crops), there has also been a rise in interest in drought tolerance of these species. Examples are *Populus balsamifera* (balsam poplar), *Panicum virgatum* (switchgrass), and *Jatropha curcas* (jatropha). Energy crops are often envisaged for growth on marginal land, where often the problem is lack of water. One of the principal portals to genomic information relevant to bioenergy crops is the phytozome portal.\(^{10}\) Others are described by Ref. [47].

Evidence suggests that combined heat and drought stress can cause disproportionate damage to important crops compared with either stress individually (see Ref. [48]). Therefore, understanding dual stress tolerance such as heat and drought in crop plants in multiple locations over multiple seasons has become a top priority in agricultural research. Transgenic plant technologies derived from dual stress tolerance could enable farmers around the world to maintain higher yield and productivity over variable and adverse environmental conditions [49].

**Too much water**

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% of the global supply of rice. In total, some 30–40 million hectares get submerged, and this happens roughly every 3 years. Most rice varieties can tolerate only a few days of submergence and die after about a week. With traditional lowland rice, when flooded the plant reacts by spurring growth to get above the water, it continues to grow during the

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\(^8\) [http://www.gramene.org/](http://www.gramene.org/)
\(^{10}\) [www.phytozome.net](http://www.phytozome.net)
flooding, and finally runs out of nutrients and dies. Variety SUB1A does not grow while flooded and starts growing again after the flooding has subsided (Figure 11.2). In this case a single mutation is involved in tolerance.

SUB1A has been introduced into several mega-varieties of rice through MAS and backcrossing without apparent adverse effects on the plants [51]. 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 nonsubmerged conditions. SUB1 is gradually being introduced to all varieties developed for lowland ecosystems by the International Rice Research Institute, and several national programs are also introducing the gene into locally adapted varieties. To date, over 4 million farmers have been reached with seeds of SUB1.

Decoupling agriculture from fossil fuels
Nitrogenous compounds in fertilizers are major contributors to waterway eutrophication and GHG emissions, and the Haber–Bosch process for making fertilizers is very energy-intensive. It consumes 3–5% of the world’s natural gas production and releases large quantities of CO\(_2\) to the atmosphere [52]. When the price of Brent crude oil rose from around $50 per barrel to about $110 by January 2013, the prices for ammonia in Western Europe and the Mid-Western corn belt in the United States roughly tripled over the same period.\(^{11}\)

Several efforts are ongoing in a tantalizing research area—creating plants that make their own fertilizer. 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 [53]. This project aims to reengineer the cyanobacterial

\(^{11}\) http://marketrealist.com/2013/02/brent-oil-moves-nitrogenous-fertilizer-prices/
machinery to fix nitrogen using solar energy as a first step toward transferring the machinery into plants themselves. This has the potential to revolutionize agriculture and significantly decouple it from the fossil fuels industry.

The oil palm: a classic bioeconomy quandary, and the power of genomics

Oil palm not only provides 45% of the world’s edible oil, but the oil is well suited for use as biodiesel. By 2019, Indonesia and Malaysia are forecast to nearly double their production of biodiesel [54]. The central issue of food versus energy security is clearly a concern, and there are also social and environmental issues around its overexploitation in South East Asia [55]. Therefore, in this one crop, are illustrated some of the toughest bioeconomy issues.

The oil palm genome sequence was published by Singh et al. [56]. 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) (Figure 11.3). 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. [56] 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, which is excellent news for the industry, the rainforest, 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 6 years to identify whether an oil palm plantlet is a high-yielding palm. Even with selective breeding, 10–15% of plants are the low-yielding *dura* form due to uncontrollable wind and insect pollination, particularly in plantations without stringent quality control measures [57].

Accurate genotyping such as this has a critical implication for a bioeconomy. Enhanced oil yields can optimize and ultimately reduce the acreage devoted to oil palm plantations, providing an opportunity for conservation and restoration of dwindling rainforest reserves [58].
Fisheries and aquaculture

Stresses on land use could be alleviated by higher fish consumption (e.g., Ref. [27]). Seafood is already the highest value globally traded food commodity. There are many potential applications of genomics to sustainable wild and farmed fish production. Here a small selection of high-priority applications is outlined.

Genomics and the fishing industry

The social, economic, and environment contributions of fisheries are known to be under threat. Numerous wild fish populations are either overexploited or are in precipitous decline. Wild fisheries should therefore be regarded as “not necessarily renewable,” and many are threatened. Many universal difficulties associated with wild fisheries are related to fish species misidentification. Incorrect identification can lead to errors in estimating numbers of fish species and the actual magnitude of fish stocks, with consequences for fisheries management and the fishing communities. Standardized DNA barcodes that are unambiguous, widely applicable, and globally accessible to the nonexpert can address such identification difficulties, along with other practical fishing industry problems, such as traceability, illegal fishing, and fish fraud [59].

Figure 11.3 The Shell gene is responsible for the oil palm’s three known shell forms: dura (thick); pisifera (shell-less); and tenera (thin), a hybrid of dura and pisifera palms [56]. Tenera palms contain one mutant and one normal version, or allele, of Shell, an optimum combination that results in 30% more oil per land area than dura palms [57].
Aquaculture and genomics

Aquaculture production has continued to grow annually at around 6–8%. Today, farmed seafood production (around 60 million tonnes) exceeds that of wild fisheries and has significant potential for future growth.

High-priority traits for farmed fish are the development of single-sex populations and improving disease resistance. Production of single-sex stocks (either male or female, depending on the species) is desirable in most commercial production to cut the cost of farming. In any commercial fish species, one sex usually reaches maturity and market size more quickly than the other; it is often the female (e.g., halibut), but not always, as in the case of Nile tilapia. Genomics is contributing to understanding the sex determination mechanism, as illustrated by two recent papers applying restriction-associated DNA (RAD) sequencing analysis to these two very important farmed species.

Palaiokostas et al. [60] described assays for sex-associated DNA markers developed from RAD sequencing analysis to help implement single-sex female halibut production. The same technique was used by Palaiokostas et al. [61] to identify a reduced candidate region for the sex-determining gene(s) and a set of tightly sex-linked SNP markers in male Nile tilapia, with no ambiguity in assigning sex.

Salmon genomics: a very special case

Salmonids, in particular Atlantic salmon, are among the most important aquaculture species. In 2010, approximately 1.5 million tonnes of Atlantic salmon were produced from farms worldwide, corresponding to a value of just over $7.8 billion [62]. It is an important bioeconomy species due to the low GHG emissions associated with farming salmon.

The genomic resources for Atlantic salmon are among the most extensive of all aquaculture species and include several genetic maps, a physical map, an extensive expressed sequence tag database of approximately 500,000 tags, and several microarrays [63]. In June 2014, the International Cooperation to Sequence the Atlantic Salmon Genome announced completion of a fully mapped and openly accessible salmon genome, which is housed at its own website. Some of the expected outcomes of this research are: understanding the attacks by viruses and pathogens on salmon and to produce new vaccines to reduce losses through disease; applications for food security and traceability and brood-stock selection for commercially important traits; and better understanding of the interactions of farmed salmon with wild counterparts.

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13 http://www.icisb.org/atlantic-salmon-genome-sequence/
Selective breeding of salmon will be more targeted and efficient. This could, for example, select for individuals that are more resistant to disease and parasites, and select fish that grow more quickly while being adapted to new feed types (see the chicken example of “more from less”). In the longer term, genomic knowledge should help streamline the aquaculture industry while providing consumers with healthier farmed salmon, produced with as little environmental impact as possible.

In the case of salmon, then, the power of relatively small public research funding of genomics to transform an industry is illustrated. In this case, many of the problems of the industry can be addressed through a single tool, which makes genomics unique as a solution provider.

INDUSTRIAL BIOTECHNOLOGY—REPLACING THE OIL BARREL

The new industrial biotechnology is largely about the bio-based production of fuels, chemicals, and plastics. In most cases, the products already exist, made from fossil resources through oil refining and petrochemistry. There is no shortage of crude oil or natural gas, and replacing the oil barrel will take decades. However, increasing political pressure and societal awareness over climate change and energy security may necessitate its replacement long before crude oil becomes scarce.

Much of the focus on GHG emissions reductions has been in the energy industry and transport, which spurred the biofuels and bioenergy initiatives. However, the chemicals sector is the largest industrial energy user, accounting for one-tenth of global energy use [64] and is the third largest industrial source of emissions after the iron and steel and cement sectors [65]. This is one of the main drivers behind the development of a bio-based chemicals industry.

One of the questions asked frequently is: how much substitution of fossil-derived chemicals and plastics is possible using bio-based equivalents or new molecules? It has now been demonstrated that even completely unnatural compounds can be manufactured using microbial cells (e.g., Ref. [66]) and the technique of metabolic engineering. The open question regarding the ability to replace the entire oil barrel is becoming an increasingly important political question. Some of the classes of chemicals in the literature that can be made through metabolic engineering of microbial strains are shown in Figure 11.4.

The list of successes is increasing, and there is tentative evidence that the time from conception to production (the innovation cycle) is decreasing. However, what is achievable in the research laboratory may never see commercial mass production. Bio-based production of aromatics, an extremely important class of industrial chemicals, is problematic, due partly to their toxicity to microbial cells. However, prior to the global dominance of the petrochemicals industry, wood refineries existed in
significant numbers (e.g., Re. [67]) and lignocellulose is also a potential source of aromatic compounds.

It is foreseeable that the combination of wood and “green” chemistry with microbial metabolic engineering could be a potent force in the eventual replacement of the oil barrel. Coal, although still vitally important as a feedstock for electricity generation, will need to be replaced in the long term to honor the $2^{\circ}$C obligation. However, as it becomes less popular as a fuel, it may achieve a renaissance as a source of aromatic chemicals.

The ultimate manufacturing model is the integrated biorefinery, where multiple classes of bio-based products are made from multiple sources of biomass. In these days of the infancy of bio-based production, there is a preponderance of single substrate, single product biorefineries. A great danger for such facilities is that if the price of the feedstock changes rapidly, the facilities can be put out of operation. This has already happened once to soy bean biodiesel production in Iowa. The greater the number of feedstocks that can be processed at a single facility, the greater the buffer against price volatility.

**Biobased 1,3-propanediol: a metabolic engineering classic**

Globally, the 1,3-propanediol (1,3-PDO) market is expected to grow from an estimated $157 million in 2012 to $560 million by 2019, with a compound annual growth rate of 19.9% during this period. It can be used in many synthetic reactions and has uses in solvents, adhesives, resins, detergents, and cosmetics. It is especially well known as a monomer for the synthesis of polytrimethylene terephthalate, a
polyester with excellent properties for fibers, textiles, carpets, and coatings. The bio-based equivalent, now fully commercialized, has very significant environmental performance advantages compared to the petro-based counterpart.\textsuperscript{14}

Its bio-based production was perfected in \textit{Escherichia coli}. One of the considerations for working in \textit{E. coli} is strains based on \textit{E. coli} K12 are eligible for favorable regulatory status in the United States. The engineered strain relies on a carbon pathway that diverts carbon from dihydroxyacetone phosphate, a major pipeline in central carbon metabolism, to 1,3-PDO.

During the metabolic engineering, the two most fundamental changes described were (Figure 11.5):

1. To remove a theoretical yield limitation, the phosphotransferase system was replaced with a synthetic system comprising galactose permease (\textit{galP}) and glucokinase (\textit{glk}); both genes are endogenous to \textit{E. coli}.
2. Triosephosphate isomerase (\textit{tpi}) was deleted in an early construct (part (a) in Figure 11.5). But this also imposed a yield limitation. To overcome this, \textit{gap} (glyceraldehydes 3-phosphate dehydrogenase) was down-regulated, which, along with the reinstatement of \textit{tpi} (part (b) in Figure 11.5), provided an improved flux control point.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Figure_11.5.png}
\caption{Metabolic engineering for the production of 1,3-propanediol [68]. (a) An early construct; (b) a later construct with improved yield. GAP, glyceraldehyde 3-phosphate; DHAP, dihydroxyacetone phosphate.}
\end{figure}

\textsuperscript{14} \url{http://www2.dupont.com/Bio-based_Propanediol/en_CN/}
Along with other changes, the end result was a metabolically engineered organism that produced 1,3-PDO at a titer of 135 g/l.

**Sugar to plastic through metabolic engineering and fermentation**

Polylactic acid (PLA) has been considered a good alternative to petroleum-based plastic because it possesses several desirable properties such as biodegradability and biocompatibility. The major driver for its production is for large-scale use in fibers and fabrics. For example, it is being used in car interiors, replacing plastics with greater GHG emissions. Current manufacturing consists of fermentation to produce lactic acid followed by one of two major chemical routes to the polymer, both of which are difficult and either use high temperatures and solvents or heavy metal catalysts [69]. But there is no existing natural bacterial route to PLA. However, Jung and Lee [70] described efficient production of PLA by a direct fermentation of glucose without a chemical step (Figure 11.6) in a metabolically engineered *E. coli* chassis strain.

![Diagram showing metabolic pathways for glucose fermentation to PLA in E. coli](https://example.com/diagram)

**Figure 11.6** Direct fermentation of glucose to PLA in *E. coli*, replacing the chemical polymerization step [70]. The overall metabolic network is shown in blue together with the introduced metabolic pathways shown in black for the production of the PLA homopolymer and the P(3HB-co-LA) copolymer in *E. coli*. The genes with cross marks shown in black represent the chromosomal gene inactivation and the elimination of *F* plasmid shown in the box, and the genes with dashed arrows shown in black represent the overexpression of the genes by chromosomal promoter replacement. For interpretation of the references to color in this figure legend, the reader is referred to the web version of this book.
Consolidated bioprocessing

There are many areas of research required to bring about this revolution in manufacturing, especially in both genomics and bioinformatics. One area receiving attention is to combine several bioprocess functions into a single biocatalyst (the so-called consolidated bioprocessing, CBP), rather than to rely on multiple, expensive hydrolytic enzymes or thermal processes for pretreatment of cellulosic biomass to fermentable sugars. The United States Department of Energy (US DoE) opined that CBP technology will lessen the complexity, cost, and energy intensity of the cellulosic biorefinery [71], endorsing the view that this technology may offer the ultimate low-cost configuration for cellulose hydrolysis and fermentation. Biomass conversion allied to synthetic biology has been termed “a match made in heaven” [72]. An example of the potential was demonstrated by Bokinsky et al. [73], in which an engineered *E. coli* was able to utilize pretreated switchgrass to produce three advanced biofuels (Figure 11.7).

The food versus fuel controversy, and avoiding it in future

The rapid expansion of the bio-ethanol industry based on corn (maize) as a feedstock (first-generation biofuels) was accompanied by a debate concerning the role of biofuels in food prices increases around 2008, the so-called food versus fuel debate (e.g., Ref. [74]). Evidence linked first-generation biofuels to the price spike, some of it

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**Figure 11.7** Engineering *E. coli* for use in consolidated bioprocessing. Cellulose and hemicellulose were hydrolyzed by secreted cellulase and hemicellulose enzymes into soluble oligosaccharides (blue). β-Glucosidase enzymes (red) further hydrolyzed the oligosaccharides into monosaccharides, which were metabolized into biofuels via heterologous pathways (from Ref. [73]). For interpretation of the references to color in this figure legend, the reader is referred to the web version of this book.
showing a marginal effect among a host of factors, but the actual extent of the linkage will probably never be known. Many studies (e.g., Refs [75—78]) have arrived at the view that there were several causes, interacting in a complex way, and that biofuels were only a part of the cause. However, the quest was already under way to use organic waste sources as feedstocks in future biorefineries. This avoids the use of food crops for biorefinery operations. The waste materials that are available in large quantities are the “cellulosic” agricultural and forestry wastes, municipal solid waste (MSW), including food wastes, and waste industrial gases.

**Cellulosic biorefineries**

The arrival, albeit in small scale, of cellulosic biorefining heralds a landmark achievement. The first commercial scale cellulosic ethanol (second-generation ethanol) plant in Europe is now open in Crescentino, Italy, with the aid of public finance. At least three plants will be open in the United States in 2015, all built with public support. The success of these plants could be critical to the future of cellulosic ethanol [79] and further expansion of the biofuels industry.

One of the more significant challenges in utilizing the vast global lignocellulose resource is the need for large quantities of glycoside hydrolase enzymes to efficiently convert lignocellulose, hemicellulose, and cellulose into fermentable sugars (Table 11.2).

<table>
<thead>
<tr>
<th></th>
<th>Glucose</th>
<th>Xylose</th>
<th>Arabinose</th>
<th>Mannose</th>
<th>Lignin</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hardwood</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Birch</td>
<td>38.2</td>
<td>18.5</td>
<td>—</td>
<td>1.2</td>
<td>22.8</td>
</tr>
<tr>
<td>Willow</td>
<td>43.0</td>
<td>24.9</td>
<td>1.2</td>
<td>3.2</td>
<td>24.2</td>
</tr>
<tr>
<td><strong>Softwood</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spruce</td>
<td>43.4</td>
<td>4.9</td>
<td>1.1</td>
<td>12.0</td>
<td>28.1</td>
</tr>
<tr>
<td>Pine</td>
<td>46.4</td>
<td>8.8</td>
<td>2.4</td>
<td>11.7</td>
<td>29.4</td>
</tr>
<tr>
<td><strong>Grasses</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wheat straw</td>
<td>38.2</td>
<td>21.2</td>
<td>2.5</td>
<td>0.3</td>
<td>23.4</td>
</tr>
<tr>
<td>Rice straw</td>
<td>34.2</td>
<td>24.5</td>
<td>n/d</td>
<td>n/d</td>
<td>11.9</td>
</tr>
<tr>
<td>Corn stover</td>
<td>35.6</td>
<td>18.9</td>
<td>2.9</td>
<td>0.3</td>
<td>12.3</td>
</tr>
</tbody>
</table>

Figures are percentage of total dry weight. Glucose is mainly derived from cellulose, xylose, arabinose, and mannose from hemicellulose. Lignin is comprised mainly of phenolics.

n/d, not determined; —, below detection limit.

Source: From Ref. [80].

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The harsh conditions used in the pretreatment of the raw material release fermentation inhibitors including weak organic acids (particularly acetic and formic acids), furan derivatives, and phenolic compounds (there are several reviews, e.g., Ref. [81]). To improve the fermentation ability of industrial *Saccharomyces cerevisiae* yeast strains for ethanol production, several strategies have been applied to overcome the effect of inhibitors. These approaches include: controlling inhibitor concentrations during the fermentation [82]; a mutagenesis and genome shuffling approach [83]; and the overexpression of genes encoding enzymes that confer resistance toward specific inhibitors [84].

The ability of *S. cerevisiae* to convert glucose to ethanol is the basis of much of the biofuels industry, with a theoretical ethanol yield of over 160 g/l [85]. It cannot, however, ferment C5 (pentose) sugars efficiently to ethanol, and xylose and arabinose may constitute up to 30% of the sugars that can be derived from lignocellulose. And yet it has a full xylose metabolic pathway [86]. There are other yeasts that can utilize C5 sugars, but their yields and productivity of ethanol are low by comparison. *S. cerevisiae* is also a GRAS organism (generally regarded as safe), with favorable regulatory status. As a result there is high interest in metabolic engineering of *S. cerevisiae* to improve C5 fermentation to ethanol (e.g., Ref. [87]).

Arguably more is known about *E. coli* than any other organism, and K12 strains also have favorable regulatory status. However, despite its flexibility and its very low risk level, it is not always possible to ensure efficient transcription/translation of a heterologous gene in *E. coli*, and post-translational protein modification does not occur in prokaryotic production systems. The *E. coli* catabolite repression limits simultaneous utilization of multiple carbohydrates [88], making industrial bioprocessing less efficient. Hence the development of specialized eukaryotic production hosts such as yeast. Some limited progress has been made in the co-utilization of mixed sugars for industrial purposes, both by metabolic pathway implantation and by isolation of catabolite repression-negative microorganisms (reviewed by Ref. [89]).

**MSW as a feedstock for biorefining**

Much of the organic matter in MSW is suitable as a fermentation feedstock. It is of a very mixed nature, and in its solid form would be extremely difficult to maintain as an on-specification feedstock for biorefining. However, virtually any form of organic matter can be converted into syngas through high-temperature gasification, and this can be done with the organic fraction of MSW. The first stage in MSW biorefining, then, is gasification, followed by syngas fermentation.

Although globally there are 1.3 billion tonnes of MSW, about 420 million tonnes are suitable for use in the current first generation of MSW biorefineries. That is the equivalent of 160 billion liters of renewable fuels from one sector alone, more than doubling the addressable market for biofuels with just the one feedstock.
MSW biorefining addresses two other societal challenges, the diminishing supply of geologically suitable landfill sites, and the ever-increasing headache for cities of how to deal with waste (Box 11.1). The future products include those of lower value, such as heat and power, through to higher value materials such as chemicals and pharmaceuticals. This highlights that environmental and economic aspirations need not contradict each other.

**BOX 11.1 Edmonton’s solution to landfelling**
The City of Edmonton is moving from 60% waste recovery for recycling into other materials, already a high proportion, to 90%, arguably the best in the world. This is to be achieved via a MSW biorefinery that converts residuals from the City of Edmonton’s composting, recycling, and processing facilities, waste that would otherwise be landfilled, into biofuels. The annual amount of this refuse-derived fuel is 100,000 tonnes.

From the Edmonton municipality point of view, it costs roughly CAD 70 per tonne, in fully loaded costs, to open up a new landfill. When a combustion technology to generate some power and slow the rate at which the site is filled to capacity is added in, that rises to around CAD 90 per tonne of waste. The commercial deal with Edmonton calls for a 25-year, CAD 45 per tonne deal that ultimately converts 30% of the city’s waste stream to liquid fuels and chemicals. The first products are ethanol and methanol.

Beyond Edmonton, cities that have expressed strong interest in finding solutions sooner rather than later to landfelling problems include Philadelphia, Toronto, and Los Angeles. In 2015 there is a commitment to complete a commercial-scale facility in Varennes, Quebec, an option to double the capacity in Edmonton which the city and company are now mutually exploring, and a DoE-sponsored commercial-scale project in Pontotoc, Mississippi, that was conceived out of funds from the Recovery Act.

Source: Various, and Biofuels Digest [90].

**Food waste, a major component of MSW**
A huge amount of food is wasted unnecessarily. In particular, bread is wasted in large amounts, with a fraction that falls between 12% and 39% of MSW among different countries. In the United Kingdom, it is the largest contributor to food waste; 32% of all bread purchased is dumped when it could be eaten.16

Leung et al. [91] investigated the feasibility of fermenting waste bread to succinic acid. The resultant succinic acid production bioprocess gave an overall yield of 0.55 g succinic acid per gram of bread, at the time the highest yield among other food waste-derived media reported. Succinic acid is a precursor for many chemicals, with a production capacity of 30,000 tonnes per year and a corresponding market value of $225 million [92].

Fermenting industrial waste gases to bio-based products
Industrial waste gases, such as CO₂ and CO, are starting to be used as feedstocks for fermentation. This has the enormous advantage of decoupling bio-based production from food production. A good example is the use of steel mill off-gases, especially highly toxic CO, to produce valuable chemicals [93], and in the future, a jet fuel. Photosynthetic and nonphotosynthetic biocatalysts are being developed that rely on metabolic engineering to improve yields and titers. Similarly, Calysta17 of Norway uses natural gas-fed fermentation to produce feed-quality protein with high nutritional value for use in aquaculture. There are two means of carbon capture from waste gases for industrial purposes to consider, photosynthetic and nonphotosynthetic.

Photosynthetic carbon capture from waste gases
Much more attention has been given to photosynthetic processes and marine algal applications in particular. If successful, algae could deliver six to ten times more energy per hectare than conventional cropland biofuels while reducing carbon emissions by up to 80% relative to fossil fuels [94].

Cyanobacteria and algae grow faster than terrestrial plants and have simpler genetic backgrounds, which are easier to manipulate [95]. Despite the availability of a relatively large number of completed genome sequences, applications of synthetic biology in cyanobacteria and algae have significantly lagged behind those in E. coli and yeast.

Despite the obvious potential, there are several technical barriers and many clear targets for synthetic biology studies [96]. There is a serious lack of chassis strains. There is a lack of cyanobacterial standardized parts, and it cannot be assumed that E. coli or yeast parts will perform the same way in cyanobacteria (or vice versa). Indeed, performance will differ across different cyanobacterial species.

Transformation efficiencies need to be improved. In vivo restriction activities are an important barrier to introducing foreign DNA into cyanobacterial cells. A horizontal barrier is that solar conversion efficiencies are low, with yields around 5—7% during the growing season and around 3% in bioreactors on an annual basis [97]. In photo-bioreactors, excessive photon capture by the cells in the surface layer can block the light availability to the cells underneath [98]. Ribulose bisphosphate carboxylase is an essential enzyme in photosynthetic carbon fixation, but the reaction is slow. However, the carbon fixation efficiency can be greatly increased [99]. Despite early progress, synthetic biology in cyanobacteria and algae is in its infancy.

Nonphotosynthetic carbon capture from waste gases
Microorganisms capable of fermenting syngas are ubiquitous. They have diverse metabolic capabilities, resulting in the formation of a variety of desirable native products

17 http://calystanutrition.com/nutrition/
such as acetate, ethanol, butanol, butyrate, formate, and H₂ [100] but not at industrial-scale efficiency. The vast majority of syngas fermenting organisms are anaerobic acetogens, which have a chemoautotrophic mode of metabolism [101].

Developing technologies based on purely chemoautotrophic organisms that utilize CO₂ and other waste gases for producing bio-based chemicals and fuels is attractive but technically very challenging. Six natural carbon fixation pathways are known so far, of which five are found to some extent in chemoautotrophs. Of these, the Wood–Ljungdahl pathway seems to be the most efficient in bio-based production conditions [102]. What may turn out to be critical is that it also can operate under heterotrophic conditions [100].

The choice is similar to the choice in other bio-based production technologies—if contemplating the introduction of a complete carbon fixation pathway into a prokaryotic host, whether to introduce a natural pathway or a synthetic one. And the dilemma is also the same—natural pathways have been optimized for the survival and reproduction of the native organisms in their natural environments, not for the survival in the artificial, extreme environment of a bioreactor, using high substrate concentrations to make high titers and yields of desired industrial products.

However, the task represents another classic for synthetic biology. Carbon fixation requires a relatively large set of genes, most of which involve complex, largely unexplored regulation [103]. Then there are the familiar tasks, the creation and insertion of the genes necessary to make the industrial product and the removal of competing or interfering genes or pathways. Additional complications arise from: anaerobic or microaerobic conditions; suitable redox environments; specialized metals chaperones; and membrane systems for ATP coupling [102]. All this also requires a synthetic biology strategy that minimizes the complex regulatory systems. As with many other bioeconomy applications of synthetic biology, the promise is great but the tasks ahead gargantuan.

As examples of the promise, ethanol production from CO is considered to be a viable approach to low-carbon fuel production, and at least three companies are seeking to develop the technology as a commercial process. The biochemistry and metabolic engineering of gas fermentation for biofuels was reviewed recently [104]. Köpke et al. [105] demonstrated the production of 2,3-butanediol from waste gases. A recent patent filing described the production of one or more terpenes by recombinant, acetogenic fermentation of CO [106].

**The short-chain alkenes: the powerhouse of the petrochemicals industry**

The six short chain alkenes are the main building blocks in modern petrochemistry. They are used in the plastics industry, for example, for producing polypropylene or polyethylene (Table 11.3). These short chain alkenes are currently produced by catalytic cracking of petroleum products and natural gas.
A patented method [107], using techniques of synthetic biology, describes the production of alkenes from a 3-hydroxyalkanoate by enzymatically converting it into the corresponding 3-phosphonoxyalkanoate, and using a second enzyme to convert 3-phosphonoxyalkanoate into an alkene.

In 2010, Global Bioenergies (Evry, France) generated an artificial metabolic pathway to isobutene from glucose. Isobutene is a gas, and its recovery from a fermenter is therefore simplified. There is no product toxicity, no feedback inhibition, and the downstream processing is inexpensive. Because of the central role of these compounds in the modern petrochemicals industry, perfecting bio-based versions of the short-chain alkenes would give enormous impetus to replacing the oil barrel.

**CHALLENGES ON MANY FRONTS**

If we are truly at the start of the era of bio-manufacturing and a long journey to a new energy order, then there is also an extremely complex web of new policy to be developed. Not only does this cover the entire supply and value chains, it brings in other aspects such as education and training, and public opinion. Many of the technologies remain to be proven at full-scale, and investors find scale-up very risky. A constant message from industry is the need for policy consistency and stability: most of the investments for this new future will have to come from the private sector, but public policy stability is needed to de-risk the investments. There will be a need for years to come for public policy that supports these developments if society feels that it is necessary to go down this path. In sustainability terms, there are very few options, if any, other than the bioeconomy that makes full use of all forms of biomass and waste materials in a post-fossil era.

**Biomass sustainability**

At the very heart of all this is biomass sustainability [108], given the competition for its use between food and industrial production. At present there is no consensus on what the metrics for biomass sustainability should be [109]. Therefore it cannot be
accurately assessed how much biomass can actually be grown sustainably. The very first international biomass sustainability disputes have already arisen. Currently the regulatory framework is a confusing patchwork.

**Public opinion**

One of the toughest issues in Europe relating to the roles of -omics technologies will be gaining public support, as negative reaction to genetic modification testifies. Something highlighted here is that application of genomics technologies without genetic modification or synthetic biology can drive progress toward a bioeconomy. In industrial production, contained use (in bioreactors) regulation pertains. However, the greatest difficulties are related to deliberate release of genetically modified crops.

**Education and training**

To take these aspirations to realities will need a workforce qualified in skills that are not currently in profusion. Bioeconomy poses a long-recognized conundrum for higher education—the need for breadth and depth, necessitating multidisciplinary higher education. Most governments face this difficulty as science and engineering tend to be taught by discipline. Biologists who understand engineering are few but increasing in number. Adding business skills may also be necessary. Bioinformatics is rapidly becoming the -omics bottleneck, given the progress in high-throughput sequencing. And yet, too rapid educational progress could create oversupply (e.g., Ref. [110]). Not only do new educational programs need careful design, but also careful monitoring.

**CONCLUDING REMARKS**

In the wake of the HGP and the rush to high-throughput genome sequencing, the impact of genomics outside of human health is comparatively underreported. We do not ignore human health as a factor in a bioeconomy—part of the problem is, in fact, the ageing population and the associated challenges to health care. By 2050, the International Monetary Fund has estimated that the European Union will move from 4:1 working people-to-elderly (currently) to only 2:1 [111], with serious economic consequences.

For this chapter, however, we chose to focus on other sectors that are vital to the future bioeconomy: the trinity of food, energy, and chemicals. Much of the world has embarked on energy reform. It is clearly a long, expensive process. It is harder to foresee a society with drastic reductions in chemical products without large lifestyle changes. All three currently are highly dependent on fossil fuel resources, and that will ultimately change. Nevertheless, the futures of food, energy, and chemicals are
interlinked, which is essentially the overarching challenge for policymakers and society. With sufficient political and societal will the -omics technologies could help make the necessary transitions easier to manage.

**Gestalt or laissez faire?**

This generation is the most privileged of all time. Decades of refinement to petrochemical processes has led to the current “way of life,” with a seemingly endless stream of new products that make life more convenient. Less people are hungry now than ever before. A result, however, is a set of grand challenges that threaten this way of life. The history of climate change negotiations shows just how difficult it has been to get acceptance of the fact that our planet is heading in the wrong direction as the result of our own hand. To correct matters requires Draconian action over long time-scales; history tells us that society strongly resists a change in the existing order [112]. Nevertheless, all the evidence being accumulated points to a need for action. The bioeconomy concept holds some of the answers.

So we conclude with a question:

“What would you want the high school history text books of 2115 to say about our generation?”

**ACKNOWLEDGMENTS**

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