An Empirical Analysis of the Industrial Bioeconomy: Implications for Renewable Resources and the Environment

Brandon Morrison and Jay S. Golden*

An empirical analysis was undertaken to quantify the utilization of the primary, first-generation agriculture and forestry feedstocks within the industrial bioeconomy. Institutional policies and incentives, and their role in driving the bioeconomy are also explored. In doing so, we present a detailed analysis of global agricultural and roundwood forestry production, including both intermediate and final uses. In addition to deciphering the internal flows of commodities within the bioeconomy, we present the spatial distribution of key industrial bioeconomy feedstock crops and their influence within the global economy, including flows in exportation and importation across ten geographical regions. Finally, along with the many advantages for industrial biofeedstocks, there are also environmental trade-offs. The results from this examination will equip researchers, industries, and governments with a superior ability to address the multi-dimensional feedbacks and synergies of the bioeconomy, as well as predict potential areas of risk and those that may prosper from future production increases.

Keywords: Bioeconomy; Industrial biotechnology; Renewable resources; Life cycle analysis; Sustainable systems

*Contact information: Division of Earth & Ocean Sciences, Nicholas School of the Environment-Duke University; Duke Center for Sustainability & Commerce, 140 Science Drive, Gross Hall Box 90467, Duke University, Durham, NC 27708 USA; *Corresponding author: Jay.Golden@Duke.edu*

INTRODUCTION

The utilization of biological feedstocks in the production of transportation energy, including both ethanol and biodiesel, has been a conventional practice for an extended period of time. Similarly, the environmental, economic, and social benefits and impacts associated with the use of biofuels have been deliberated in the public domain for an equal length of time. These debates have included weighing the environmental benefits of biofuels in comparison to food security and price spikes, such as those affecting corn in 2007 (Rosegrant 2008; Wise 2012), land use changes (Searchinger *et al*. 2008; Plevin *et al.* 2010), and implications for both water quality and quantity (Varghese 2007; Thomas *et al*. 2009). However, in the present and future we will be witnessing an increased acceleration and intensification of biological feedstocks worldwide for industrial purposes (Lotze-Campen *et al.* 2010). Such an expansion of the bioeconomy is being driven, in part, by broader corporate and government sustainability goals.

The International Energy Agency (IEA) estimates that fuel consumption and emissions of CO_2 from automobiles will roughly double by 2050 (GFEI 2014). The transportation sector is already responsible for nearly a quarter of all CO_2 emissions from fossil fuel combustion. To date, over 50 countries have implemented mandates for the blending of biofuel with petroleum-based fuel and/or financial support measures for biofuel (IEA 2014). Two of the most comprehensive policies are found in the United States (U.S.) and the European Union (EU). In the U.S., the Renewable Fuel Standard (RFS), first established in 2005 and later expanded in 2007, mandates that both gasoline and diesel fuel blenders must incorporate minimum volumes of biofuel into their annual transportation fuel sales, irrespective of market prices (Schnepf and Yacobuccia 2013). Furthermore, the RFS stipulates that the biofuel must reduce lifecycle greenhouse gas (GHG) emissions by at least 20% relative to conventional fuel. When produced in a sustainable manner, biofuel has been shown to result in a reduction of GHG emissions (Kim and Dale 2005; Tilman *et al*. 2006; Liska *et al.* 2009; Tilman *et al*. 2009). In the EU, the Renewable Energy Directive (RED) aims at reducing the dependence on foreign oil. By 2010, the RED called for a 5.75% share of renewable energy within the transportation sector. It is projected that by 2020, every EU member state will produce a minimum of 10% of their total energy from renewable sources (European Commission 2014).

While biological feedstocks have emerged as a significant contributor to renewable transportation energy, the sustainability movement has rapidly become an additional key driver of the industrial growth of biological feedstocks in an effort to capitalize on a rising demand for environmentally friendly and renewable-based products (Maxwell and van der Vorst 2003). A result of the increase in sustainable resources has been a shift towards the increased use of biological feedstocks in lieu of non-renewable petroleum feedstocks to meet the new market opportunities. A 2008 survey, conducted by Iowa State University, identified over 12,400 bio-based products that were produced or sold by nearly 2,000 manufacturers and distributors (Cox and Devlin 2010). The movement towards bio-based materials and products illustrates a shift towards increased environmental performance of both firms and products to meet demands set by consumers, the investment community, institutional buyers, and government policies (Howes *et al*. 2013).

Both industry consortiums, such as The Sustainability Consortium (TSC) and the Sustainable Apparel Coalition (SAC), as well as multi-national corporations (*i.e*., Walmart, P&G, Coca-Cola, Ford, Unilever, Nike, *etc*.) have been pioneering the use of renewable feedstocks (Golden *et al*. 2010; P&G 2011; Elk 2014). For example, Coca-Cola introduced the "PlantBottle" in 2009, a fully recyclable PET plastic bottle made with up to 30% of a sugarcane-based feedstock. The company estimated that the use of the PlantBottle would achieve a reduction of 400,000+ barrels of oil (Coca-Cola 2014). Moreover, by using the U.S. Environmental Protection Agency's (EPA) estimate for the CO_2 emissions produced per barrel of oil (EPA 2014), the PlantBottle will have led to a reduction of 172,000 metric tons (MT) of CO_2 since 2009. Similarly, the Ford Motor Company has incorporated soybean-based seats into more than three million vehicles, which has reduced annual petroleum use by greater than one million pounds (454 MT), and a reduction of over 15 million pounds (6,804 MT) of CO_2 emissions (Ford 2011). Braskem, the largest thermoplastic resin producer in the U.S., annually produces 181,437 MT of bioplastic from sugarcane ethanol. When compared to fossil fuel-based alternatives, each ton of bioplastic produced enables the reduction of approximately 2.3 MT of CO_2 (Damor 2014).

Acting in parallel to industry initiatives, many national governments have enacted policies, incentives, and regulations to expand the industrial bioeconomy in an effort towards climate change commitments, economic and job growth, as well as a means to reduce the dependence on imported non-renewable resources (Kircher 2012). In the U.S., President Obama signed Executive Order 13154 in 2009 to leverage the purchasing power of the Federal Government to expand sustainable products in the marketplace (White House 2009). The Order required that 95% of all applicable contracts meet pre-determined sustainability requirements, in addition to specifically calling for products that were energy and water efficient, and/or bio-based.

The BioPreferred program was created by the Farm Security and Rural Investment Act of 2002, and was later expanded by the Food, Conservation, and Energy Act of 2008. The program's purpose was to increase the purchase and use of bio-based products through a preferred procurement program for Federal agencies and their contractors (USDA 2013). In addition, the program included a voluntary labeling program intended to help the consumer understand what classified as a bio-based product, thereby assuring consumers of bio-based content percentages. Within the EU, the French government enacted the Grenelle II Act in 2012, which not only directly addresses corporate sustainability reporting, but also has had a strong influence on the industrial bioeconomy. Article 85 of the Act stipulated that product packaging must cover both the carbon equivalents, as well as the consumption of natural resources or impacts on natural compartments (Gaillard *et al*. 2011).

During the time period when the global population was rapidly increasing and urbanizing, coupled with a middle class expected to expand from 1.8 billion in 2009 to 4.8 billion by 2030 (Kharas and Gertz 2010; Ernst and Young 2013), there was a demand for understanding the implications of an increased global utilization of biological resources to achieve improved environmental performance of industrial and consumer products. Current volumetric and spatial flows of biological feedstocks and their industrial uses provide unique insight, which can reduce unintended consequences of human interactions with natural ecosystems (Bennett *et al.* 2009). Additionally, while corporations and governments are increasingly utilizing Life Cycle Assessment (LCA) modeling of the environmental trade-offs of utilizing biological feedstock, LCA methodology may lack the incorporation of broader spatial systems evaluation in the final analysis. The purpose of this study was to use empirical analysis of global agricultural and industrial use data to provide the scientific community with a broader understanding of biological feedstock flows, including those for industrial purposes. In addition, a qualitative exploration of potential implications resulting from the expansion of the bioeconomy and suggestions for further research to supplement the LCA of bio-based feedstocks and products will be investigated.

The Industrial Bioeconomy

The bioeconomy has been defined as "*the global industrial transition of sustainably utilizing renewable aquatic and terrestrial resources in energy, intermediate, and final products for economic, environmental, social, and national security benefits*" (Golden and Handfield 2014a,b). This definition provides a broad contextual meaning; however, for the purpose of this article, we will direct our focus on primarily agriculture, its flow, and its industrial uses. Furthermore, this information will expand upon environmental Life Cycle Assessment modeling.

Using the tools of biotechnology, agricultural- and forestry-based feedstocks, one can duplicate and replace the immense collection of petro- and fossil fuel-based feedstocks in current use for manufacturing consumer products, *i.e*., chemicals, plastics, textiles, cosmetics, and building materials. In the U.S. alone, 96% of all manufactured goods use a type of chemical product, and industries dependent on the chemical sector account for approximately $3.6 T in U.S. gross domestic product (GDP) (Milken Institute 2013). Furthermore, by 2030, estimates show that in the U.S. alone, there will be sufficient terrestrial biomass resources to displace 30% of current petroleum use (U.S. Department of Energy 2011). Thus, the industrial bioeconomy has significant potential in the future.

EXPERIMENTAL

Methodology

A bio-based economy can utilize a wide range of feedstocks, using various processes to convert them into a variety of different products. The focus of this study is on roundwood forestry and first-generation agricultural feedstocks; *i.e.*, agricultural crops that are traditionally grown for food and animal feed purposes. To quantify the global flows of agriculture for industrial purposes, we undertook an analysis of existing databases, including the Food and Agriculture Organization of the United Nations (FAO) (FAOSTAT 2014) and the Organization for Economic Co-operation and Development (OECD 2014), as well as published literature and first-hand interviews with representatives from global public and private sectors. Second-generation (*i.e.*, non-food crops and residues) and third-generation (*i.e.*, algae) feedstocks were excluded from this study, as there was no competition with human food consumption demands.

Commodity Classifications

Ten classifications of commodities were analyzed. These included: Roundwood Forestry, Cereals, Vegetables, Starchy Roots, Fruits, Sugarcrops, Oilcrops, Pulses, Fibers, and Treenuts. Each commodity classification could be further delineated into its individual crops (*e.g.*, sugarcrops are sugar beet and sugar cane). In sum, over 8.95 billion metric tons (B MT) of commodities were harvested in 2011, with Forestry (29% of total production), Cereals (26%), Vegetables (12%), and Sugarcrops (10%) representing the largest commodity categories. The five largest producing countries were: China (16% of global total agriculture production), India (11%), the U.S. (9%), Brazil (9%), and Russia (3%).

Land Requirements

In 2011, the production of agriculture (*i.e.*, arable land under temporary agricultural crops as well as land cultivated with long-term crops) occupied 1.548 billion hectares (B Ha) of land, which was roughly 12% of the total global land area (FAOSTAT 2015). The global area of agriculture production has not changed significantly in the past twenty years. From 1991 to 2001, the area of agriculture land actually decreased from 1.523 to 1.520 B Ha. The increase of 280 M Ha (1.84% increase) from 2001 to 2011 roughly equates to the size of Ecuador. While agricultural land increased by roughly 2% from 2001 to 2011, agricultural production increased 32%, indicating the intensification of agriculture on existing lands, as opposed to the expansion of agricultural lands.

The production of first-generation crops considered in this analysis occupied 1.2 B Ha of land, with Cereals (603 M Ha; 52.4% of total) and Oilcrops (253 M Ha; 22.0% of total) accounting for nearly three-quarters of the cultivated agricultural area. The remaining commodities occupied a combined 295 M Ha (Pulses: 80.1 M Ha; Starchy

Roots: 55.6 M Ha; Fruit: 54.8 M Ha; Vegetables: 47.5 M Ha; Sugarcrops: 30.8 M Ha; Fibers: 16.1 M Ha; and Treenuts: 10.0 M Ha).

Another 3.36 B Ha (26% of global land) were used for pasture (*i.e*., land used permanently for herbaceous forage crops, either cultivated or naturally growing) in 2011, compared with the 3.31 B Ha in 1991 and 3.42 B Ha in 2001 (FAOSTAT 2015). The loss of pasturelands from 2001 to 2011 may be because of the expansion of agricultural lands, as has been documented in the Cerrado region of Brazil (Morton *et al*. 2006).

Forests (*i.e*., land spanning more than 0.5 hectares with trees higher than five metres and a canopy cover of more than 10%, or trees able to reach these threshold criteria *in situ*; includes forestry plantations) occupied 4.03 B Ha (31% of global land) in 2011, compared with 4.16 B Ha in 1991 and 4.08 B Ha in 2001 (FAOSTAT 2015). In particular, roundwood forestry occupied 2.5 B Ha in 2011. While forest land decreased from 2001 to 2011, roundwood forestry production increased nearly 5%, from 3.37 B m^3 to 3.53 B m^3. The loss of forestry land, as well as the increase in forestry production, can be attributed to the conversion of forests to meet worldwide demand for consumer products, through both the clearing of forests for agriculture as well as the clearing of forests for pulpwood plantations (WWF 2014).

Global Flows

Though agricultural and forestry commodities are increasingly becoming the key raw materials utilized in the production of numerous consumer and industrial products, the bioeconomy has proven difficult to quantify (OECD 2009; USDA 2011). Foley *et al*. (2011) sought to quantify the bioeconomy on a global scale, determining that 62% of crop production went towards human food, 35% went towards animal feed, and the remaining 3% was distributed among bioenergy, seed, and other industrial products.

Overall, there remain gaps in the literature in quantifying the global flows of biological resources for industrial purposes, both as intermediate feedstocks and end-use products (Carus *et al*. 2013a; Carlson 2014). The primary objective of this research was to examine the global flows of biological feedstocks by quantifying the volume and spatial distribution of commodities and crops for their specific industrial purposes, their flows in trade, as well as certain environmental life cycle implications. The goal of this analysis is to serve as a platform that can support the LCA and sustainable system models that analyze trade-offs and unintended consequences resulting from the shift to a larger bioeconomy.

RESULTS

Global Industrial Uses

As presented in Fig. 1, the primary and secondary flows of global agriculture and forestry are based on the latest available combined data from 2011. Primary uses for the different commodities include the food, feed (*i.e*., for livestock and poultry), seed (*i.e*., for sowing or planting), and agricultural waste (*i.e*., during harvest and transport) sectors. In addition to documenting the global flows of primary uses, this research further extends prior works by identifying and quantifying secondary industrial uses of agriculture to include the energy, construction, apparel and textiles, paper and packaging, and the chemical sectors of the bioeconomy.

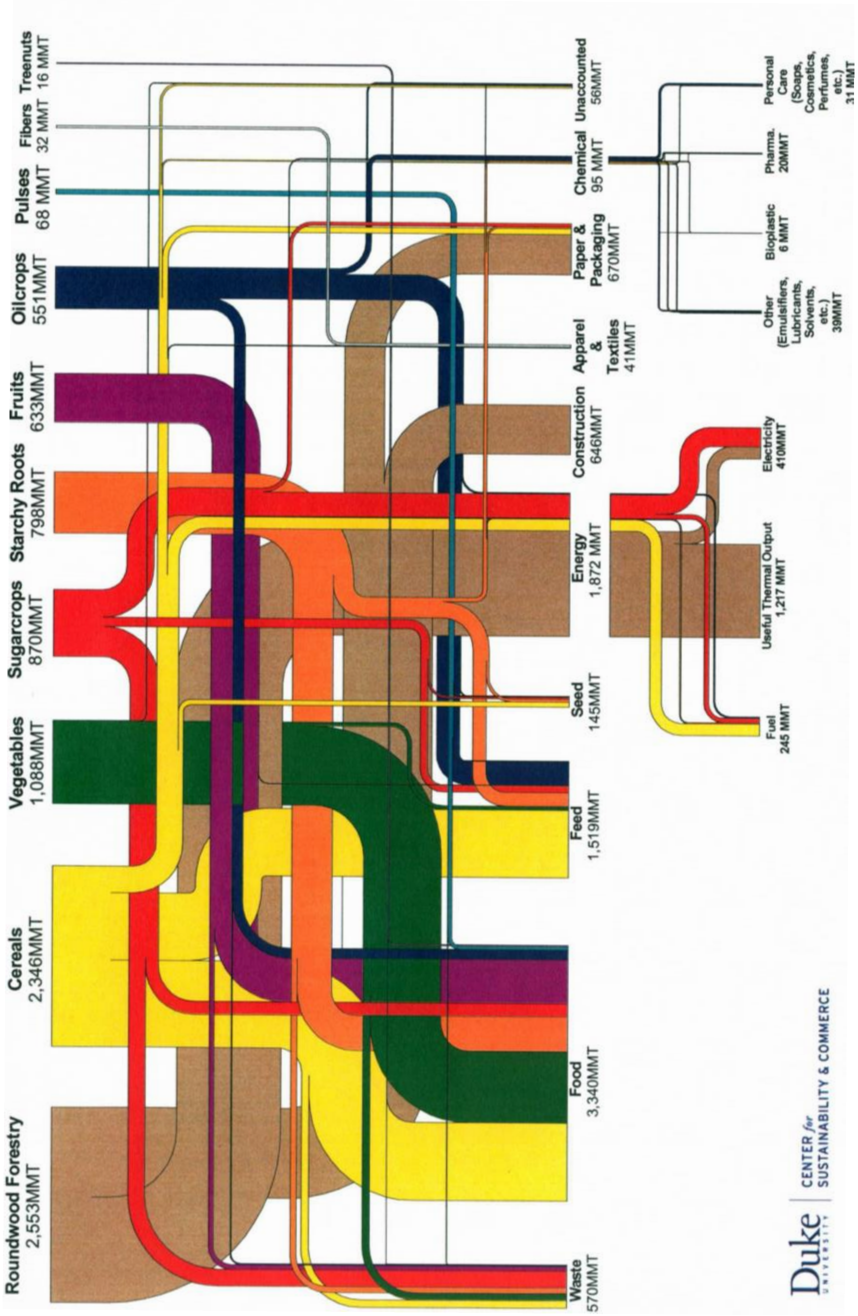

Fig. 1. Global agriculture flows for primary and secondary uses (2011). Data and author's calculations were derived from CRA 2001; Braganca and Fowler 2004; European Commission 2006; Ramachandran *et al*. 2007; Guillaume-Signoret 2007; HCGA 2009; Braskem 2009; FAO 2009a; Patil 2010; EIA 2012; UNCTAD 2012; U.S. Census Bureau 2012; J. Reed 2012; S. Moss, personal communication, January 8, 2013; UNICA 2013; ADM 2014; FAOSTAT 2014; OECD 2014.

Table 1. Commodity Classifications

Commodity Grouping	Individual Items Included within Group
Forestry – Roundwood	Pulpwood; Sawlogs; Veneer Logs; Wood Fuel; Other Industrial Roundwood
Cereals	Barley; Maize; Millet; Oats; Rice; Rye; Sorghum; Wheat; Cereals, Other
Vegetables	Onion; Tomatoes; Vegetables, Other
Starchy Roots	Cassava; Potatoes; Sweet Potatoes; Yams; Starchy Roots, Other
Fruit	Apples; Bananas; Dates; Grapefruit; Grapes; Lemons/Limes; Oranges/Mandarins; Pineapples; Plantains; Citrus Fruit, Other; Fruit, Other
Sugarcrops	Sugar Beet; Sugar Cane
Oilcrops	Coconuts; Cottonseed; Groundnuts; Olives; Palmkernels; Rape and Mustardseed; Sesameseed; Soyabeans; Sunflowerseed; Olicrops, Other
Pulses	Beans; Peas; Pulses, Other
Fibers	Cotton Lint; Jute; Fibers, Other
Treenuts	Nuts (*e.g.*, Brazil nuts, Cashews, Chestnuts, Almonds)

As presented in Fig. 1, the dominant role of roundwood forestry is for both energy (1,376 Million Metric Tons (MMT) of forestry feedstock produced from 1.2 B Ha of land) and industrial uses (1,177 MMT, with 646 MMT of roundwood produced from 726 M Ha used for construction and 530 MMT produced from 609 M Ha of land used for paper and packaging).

After accounting for waste (*i.e.*, the total production minus that lost to pre-consumer waste), the primary use of agriculture was for food (57% of the total production; 3,340 MMT of feedstocks produced from 590 M Ha of land) and feed (26% of the total production; 1,518 MMT of feedstocks produced from 432 M Ha of land). Agriculture set-aside for seed was the smallest utilization (2% of the total production; 144 MMT produced from 37 M Ha of land). Industrial use of agriculture, including energy, apparel and textiles, paper and packaging, and chemicals accounted for 13% of the total production (771 MMT of agricultural feedstocks produced from 100 M Ha of land). This was an increase of 10% from Foley *et al*. (2011), which reported that just 3% of crops went towards "other" utilizations (seed, bioenergy, *etc*.). The percentages among intermediate and end-use sectors do not add up to 100%. Therefore, a small fraction of the total production was designated as "unaccounted for," given the discrepancies among data within the databases, as well as sectors that were too small to delineate within the global economy.

When combining roundwood forestry and agriculture, 3,324 MMT of global commodity production went towards industrial purposes, produced from 2.6 B Ha of forestry and agricultural land. Energy had the largest intermediate use, with 56% of all industrial use (1,872 MMT of feedstock produced from 1.2 B Ha of land), followed by paper and packaging with 20% (670 MMT of feedstock produced from 627 M Ha of land), construction with 19% (646 MMT of feedstock produced from 726 M Ha of land), chemicals with 3% (95 MMT of feedstock produced from 26 M Ha of land), and finally apparel and textiles with 1% (41 MMT of feedstock produced from 19 M Ha of land).

Bioenergy

For the purposes of this research, bioenergy includes all renewable energy, *i.e.*, transport fuel, useful thermal output (heat), and electricity, derived from biological sources. Bioenergy production from wood, most notably in the BRIC nations of India (17% of the global wood fuel production), China (9%), and Brazil (8%), represent the largest quantity of renewable feedstock for bioenergy purposes. Wood fuel uses include traditional heating and cooking with fuelwood, heating and power production in the forest industry, and heating and power generation in power plants. By 2030, wood energy use may increase by 46% in comparison to the 2005 figures (FAO 2009b). However, this figure is somewhat uncertain, because the future demand for bioenergy may be met by both first- and second-generation biofuels.

The rapid growth in first-generation biofuel production demonstrates the potential expansion of the bio-based economy. From 2005 to 2009, liquid biofuel production, ethanol and biodiesel combined, more than doubled, going from 53 billion liters (bnl) per year to 109 bnl per year (OECD/FAO 2011). By 2020, liquid biofuel production is predicted to increase to 197 bnl per year, with ethanol production roughly four-times that of biodiesel production. By 2030, predictions call for the use of biofuels to increase to 9% (from 3% today) of the total road-transport fuel, substituting the equivalent of 6.5 M barrels of oil per day (Newes *et al*. 2012). The expansion in biofuel production is attributed primarily to policy mandates and renewable energy targets in the transportation sector (automotive and aviation) that call for a reduction in CO_2 emissions (de Jong *et al*. 2012).

Numerous technologies for generating power and electricity from bioenergy already exist, ranging from solid wood heating installations, to co-generation facilities, and large-scale biomass gasification plants. In total, bioenergy used for electricity amounted to 1.5% of global electricity generation in 2012 (IEA 2015). Going forward, this percentage is expected to increase – at an estimated 10% growth rate per year – as co-firing biomass with coal in existing coal-fired power plants is gaining traction as an option to reduce CO_2 emissions (Nakada *et al.* 2014). One prominent example is the use of wood pellets for electricity generation in the United Kingdom (Dwivedi *et al.* 2014). However, economic incentives are currently needed in order to offset cost differences between biomass- and fossil fuel-generated electricity (EIA 2014).

Biochemicals

The chemical industry, which accounts for nearly 10% of the total petrochemical feedstock use, is grouped into the following classifications: commodity chemicals (*i.e*., those manufactured in very large volumes), specialty chemicals (*i.e*., those for special uses or intermediates, such as agrichemicals, cleaning materials, and cosmetic additives), fine chemicals (*i.e*., those manufactured in smaller batches and used notably for pharmaceuticals), and polymers, which include plastics (USDA 2011). The future of the bioplastic sector is explored in greater detail in the following section.

For the past 25 years, the demand for basic petrochemicals has increased by 4.4% per year, and the demand for basic petrochemicals is expected to increase further in the future (Witte 2014). Specifically, from 2010 to 2020, global basic petrochemical production is expected to increase by 44%, from approximately 648 MMT to 936 MMT (Adams and Witte 2013). By 2030, chemical production is predicted to double (from 2010 figures) to approximately 1,800 MMT, with the vast majority of production growth occurring in the BRICS nations (CIEL 2013). Projections to 2050 note sustained annual growth of 3% for the global chemical sector (UNEP 2012). Bio-based chemicals are a sub-sector of global chemical production, representing any chemical that can be produced by processes that are reliant upon carbon from existing biological sources. Accurate quantification of global chemical product volumes is difficult, attributable to the fact that chemical products may be counted several times among the ultimate value chain of the product(s) (CEFIC 2014). Accordingly, focus on the raw material input is preferred, given that materials can only be utilized once in the production process. The EU chemical sector is explored in greater detail below to illustrate the potential growth of bio-based chemical production.

In 2011, the EU chemical sector, accounting for nearly a quarter (23.4%) of global chemical sales in value terms, utilized 90.30 MMT of organic raw materials, of which 9% (8.60 MMT) were renewable resources (CEFIC 2012; CEFIC 2014). Assuming the global chemical industry utilized a similar ratio of organic raw materials, this would equate to 34.40 MMT of renewable feedstocks that were utilized by the chemical industry in 2011. With global basic chemical production for 2011 estimated at 690.40 MMT, 34.40 MMT of renewable raw material feedstock use equates to roughly 5% of the total production, which is in line with estimates of 3 to 4% (Athanassiadou 2010; Adams and Witte 2013). Of the total renewable feedstocks, more than half (55%) was from vegetable oil, starch, sugar, and/or ethanol (CEFIC 2014). The remainder was sourced from animal fat (6%), chemical pulp (10%), natural rubber (14%), glycerol (5%), and others (9%). Cellulose chemicals produced from forestry feedstocks were excluded from the analysis as the use of residues, from both agriculture and forestry, was not considered. Furthermore, only the primary uses of agriculture and roundwood forestry feedstocks were considered, and thus when consulting the metadata for the aforementioned databases, chemical production was not listed as a primary use for roundwood forestry.

While the global chemical sector is expected to grow in the coming years, the global bio-based chemicals market is expected to experience an even greater growth. By 2025, projections call for bio-based chemicals to increase by 7 to 17% of the entire chemical market (up from 3 to 4% presently), with sales between $500 to $600 billion (Athanassiadou 2010; Vijayendran 2010). Projecting the same market percentages to 2030, this equates to approximately 126 MMT to 306 MMT of bio-based chemical production. As compared to 2011 levels of 34.40 MMT, this would require an additional 91.60 MMT to 325.60 MMT of renewable feedstock production.

Bioplastics

In the Sankey Diagram above (Fig. 1), bioplastics are depicted as a subset of global biochemical production. As industry commonly reports bioplastics as a distinct market segment, a deeper examination into the potential growth of bioplastics is undertaken in this analysis. Thus, forecasts for the global bioplastics market are predicted in addition to the growth of bio-based chemicals as noted above.

On a global scale, plastic consumption is closely correlated with per capita income (Pardos 1999). As populations grow and global affluence increases, the global plastic sector is expected to grow in parallel. By 2020, global plastic production is expected to reach 490 MMT, almost double the production from 2010 (272 MMT), with an average annual growth rate of 8.1% (Pardos 2008).

Approximately 5% of global oil production is used for the production of plastics (Bayer 2013). Bio-based plastics currently account for less than 1% of all plastics produced worldwide (Lunt 2014). Yet research has shown that greater than 90% of global plastic production is technically feasible for substitution by bio-based plastics (Vijayendran 2010).

Bio-based plastics can be produced from a variety of agricultural feedstocks, with the majority of production technologies based on carbohydrate-rich crops: cereals (*e.g.,* corn), starchy roots (*e.g.,* potatoes and cassava), sugar crops, or vegetable oils. In 2011, global bioplastics production capacity was 1.2 MMT, with bio-based polyethylene terephthalate (Bio-PET) (39%; 0.45 MMT), bio-based polyethylene (Bio-PE) (17%; 0.20 MMT), and polylactic acid (PLA) (16%; 0.19 MMT) representing the three largest segments of bioplastic production (Widdecke *et al*. 2013). Increasing consumer demand for bio-based plastics has caused rapid growth within the marketplace. By 2016, global bioplastics production is expected to see an approximate five-fold increase in production (to roughly 6 MMT), with Bio-PET representing 80% (4.80 MMT) of the global production, followed by PLA (5%; 0.30 MMT) and Bio-PE (4%; 0.24 MMT) (NanoMarkets 2012). The greatest use of Bio-PET is for bottle production (*e.g*., Coca-Cola's PlantBottle) (European Bioplastics 2012).

By 2020, it is estimated that bio-based plastic production could rise to 12 MMT (OECD 2013), representing upwards of 30% of all plastic production. More than 80% of future bioplastic production is predicted to occur in Asia and South America, which is attributable to better access to agricultural feedstock production and more favorable political frameworks, including mandates that call for greater use of compostable and/or recyclable materials (NanoMarkets 2012; Carus *et al*. 2013). The expanding global utilization of bioethanol for chemical building blocks has already led to the establishment of larger-scale production facilities in India, Taiwan, and Brazil (Dammer *et al*. 2013).

In addition to government mandates and policies, industrial initiatives are also further propelling the production and use of bioplastics in these locales. Samsung Electronics (Korea) and Toyota (Japan) have both pledged to use more bio-based materials and plastics in their products, with the latter pledging to switch 20% of all plastics used in their vehicles to bio-based plastic by 2015 (OECD 2013). In the future, Coca-Cola plans to produce a 100% renewable Bio-PET bottle (Coca-Cola 2012). Bio-PET is primarily produced from sugarcane ethanol, with approximately 5,720 MT of sugarcane required to produce 1,000 MT of Bio-PET 30 (*i.e*., 30% bio-based) (IfBB 2014). A 100% Bio-PET product would require 217,400 MT of sugarcane for 1,000 MT of Bio-PET 100 (IfBB 2014). Bioplastics produced from PLA are currently derived from corn (in the U.S.), tapioca (in Asia), or sugarcane (rest of the world) (Zhang *et al*. 2014). The direction of growth in the bioplastics sector has the potential to alter feedstock expansion regionally. For example, greater demand for Bio-PET may increase the demand for sugarcane in Brazil. Alternatively, a greater demand in Asia for bio-based plastic could increase the demand for tapioca, or alternative feedstocks, such as cassava.

Apparel and Textiles

Similar to plastics, global demand for fiber has a strong correlation with GDP growth (Qin 2014). Global fiber production, estimated in 2013 at 77.50 MMT, is presently dominated by petroleum-based synthetic fibers (62% of the market; 48.10 MMT), with the remaining production consisting of cotton (30%; 23.30 MMT), man-made cellulose fibers (7%; 5.40 MMT), and wool (1%; 0.80 MMT) (Lenzing 2013b). China (25%), India (23%), United States (13%), Pakistan (9%), and Brazil (6%) dominate global cotton production, accounting for 76% of the total production (26

MMT). Behind cotton, jute is the most utilized natural fiber, with India (55%) and Bangladesh (43%) accounting for nearly all of the 3.6 MMT of total production in 2011. Unlike cotton, which is primarily used for clothing, jute is used extensively for sacking of agricultural goods (FAO 2014).

The global textile industry is predicted to grow at an annual growth rate of 3% to 2020, fueled in part by the growth of the apparel sector (Grand View Research 2014). Similarly, clothing and apparel have emerged as the leading application segments for cellulose fiber, accounting for nearly two thirds of the total market volume. The predicted annual growth rate of bio-based fibers (9.1% per year) is more than three-times greater than that of the global fiber market through 2020 (Lenzing 2013a).

The clothing and apparel sectors are expected to continue to be the fastest growing application segments of bio-based fibers, especially as uncertainty exists over future supplies of cotton (Wexler 2014). As the global area of cotton harvested is expected to remain relatively constant going forward, and as yield increases level out, some have predicted a future "cellulose" gap in fiber production, with the demand exceeding the supply (Lenzing 2013a). As a result, from 2013 to 2020, the global demand for cellulose fiber is expected to increase by 70%, going from 5.40 MMT to 9.20 MMT (Grand View Research 2014). Clothing and apparel is the leading application of bio-based cellulose fiber, accounting for 61.3% (3.31 MMT) of all applications in 2013 (Grand View Research 2014). By 2020, this figure is predicted to grow to 9.20 MMT of all man-made cellulose fiber, with the largest consumer markets expected to be Asia-Pacific and Europe, where government regulations support the use of biodegradable fabrics.

Industry efforts are also supporting a shift towards a more sustainable clothing and apparel sector. The Sustainable Apparel Coalition, which represents more than a third of the global apparel and footwear market, is propelling further growth within the textile and apparel sectors of the bioeconomy. The Higg Index, a suite of assessment tools that standardize the measurement of environmental and social impacts throughout both a product's lifecycle and the entire value chain, is increasingly being used to make more informed decisions in relation to product development (SAC 2014). Specifically, the material assessment is aimed at ensuring companies select the most environmentally preferable materials when designing and producing products.

Construction/Built Environment

Annual per capita wood consumption in both developed and developing countries are relatively equivalent, with the difference being that the vast majority (> 80%) of wood consumption in developed countries is in industrial wood products, as opposed to developing countries that predominantly burn wood for fuel (FAO 2003; FAO 2010a; UCS 2011). Most industrial roundwood is produced in the form of sawlogs and veneer logs (comprising 60% of the total production in 2011). The bulk of this production was sourced from a relatively small proportion of the world's total forest area, principally in Asia, Europe, and the Americas. By 2030, total industrial roundwood production is expected to increase between 14% and 55%, depending on the assumed growth scenario used when making projections (Jürgensen *et al*. 2014).

Plywood and veneer sheets produced from industrial roundwood are among the most widely used wood products. The market for industrial roundwood is primarily driven by the construction industry, in which housing is the largest sector (PwC 2014). By 2020, the market size of the global construction industry will increase to $12 trillion, representing 15% of the global GDP (Schilling 2013). Developing and emerging countries are responsible for a large portion of this growth, as construction in those nations is predicted to increase 110% by 2020.

Paper and Packaging

Over the last 30 years, pulp and paper production has increased threefold through developments in industrial goods, information technologies, household consumption, and personal care products that have contributed to the demand for all kinds of paper products (OECD 2001). Increases in global population growth and GDP will continue to drive up the demand for industrial roundwood. World demand for pulp and paper, which already uses more than 40% of the world's commercial timber, is projected to increase with an annual average growth rate of 2.3% by 2020 (total projected consumption is 391,004 MMT), with the greatest growth occurring in China and South East Asia (OECD 2001).

Paper and board for packaging and other purposes (65% of the total production and consumption) generate the highest demand, followed by printing and writing paper (25%), and newsprint (10%) (FAO 2010b). Thus, a large share of the demand for paper and paperboard is dependent on the growth of the industrial and service sectors, particularly the demand for packaging materials. As geographic production volumes differ, international trade of wood products is expected to double by 2020 (FAO 2007). With the expansion of digital media, growth in newspaper circulation is expected to be minimal (Desilver 2013).

Secondary Uses

This paper focuses on first-generation feedstocks, and thus the potential of by-products in value-added pursuits is not explored in great detail. However the potential certainly exists for secondary uses of agriculture and forestry products. The most abundant biological polymer on the planet, *i.e.*, cellulose, is found in the walls of plant and bacterial cells. The primary commercial source for cellulose is wood. Specifically, the durable nature of the cellulose nanocrystals from wood by-products (*e.g.*, wood chips and sawdust) has attracted the interest of companies in the automotive, aerospace, electronics, consumer products, and medical industries (Dodson 2012). By 2020, the market for wood-derived renewable materials is estimated to be $600 B (U.S. Forest Service 2012).

DISCUSSION

Spatial Variability of the Bioeconomy

In the absence of importation of food commodities, the availability of local resources constrains population growth (D'Odorico *et al*. 2010). The same argument can be applied towards the development of the industrial bioeconomy; that is, growth in the industrial bioeconomy will either be derived from increases in local feedstock production, or attained via increases in trade for renewable feedstocks destined for industrial use. For example, Germany, which is currently the world's fourth largest chemical market (Bug 2014), must import 65% of its biofeedstocks in order to meet industrial needs (Kircher 2014). In examining the growth of the bioeconomy, we mapped the spatial distribution of four key industrial bioeconomy feedstock crops within the global economy: sugar, maize, palm oil, and soybeans.

Sugar

The top producer of sugar, in the forms of both cane and beet, is Brazil, accounting for almost 39% of the global production in 2011, as shown in Table 2. Currently, more sugar is grown for industrial purposes than is grown for food (Freitas 2014). In addition to being the largest sugar producer, Brazil is also the largest industrial consumer of sugar for biofuels. The EU, which does not have a member state within the top 10 producing regions, is second in its industrial consumption of sugar for biofuel. As opposed to Brazil, which produces and consumes sugar cane, the EU primarily utilizes sugar beets for biofuel production.

Table 2. Global Production and Utilization (in MMT) of Sugarcrops in 2011

Sugar Production (rse + FAO Uses)			Top Consumptive End-Uses					
Top 10 Producers	**Produc-tion**	**% of Global Total**	**Country**	**Food**	**Country**	**Bio-fuel**	**Country**	**Other Indus-trial**
Brazil	337.6	38.8%	India	12.0	Brazil	244.7	Brazil	38.9
India	144.2	16.6%	Pakistan	5.4	EU-28	14.1	France	6.7
China	51.3	5.9%	Brazil	3.3	Colombia	3.8	Ecuador	2.8
Thailand	38.6	4.4%	Egypt	3.1	Thailand	2.7	Madagascar	2.2
Pakistan	26.6	3.1%	Thailand	3.0	Argentina	2.2	Viet Nam	1.2
Mexico	19.3	2.2%	Viet Nam	1.4	Pakistan	2.0	Venezuela	1.4
Russia	17.6	2.0%	Nepal	1.0	Peru	1.9	Paraguay	0.8
USA	17.4	2.0%	Kenya	0.8	Vietnam	0.8	Mexico	0.7
Colombia	15.5	1.8%	Cameroon	0.4	Philippines	0.4	Guyana	0.7
Philippines	13.8	1.6%	Sri Lanka	0.4	Mozambique	0.3	Laos	0.7
Author's calculations were based on data from FAOSTAT 2014 and OECD 2014.								

Maize

As presented in Table 3, maize is a major industrial crop with significant utilization for biofuels in the United States. The U.S. is the largest producer of maize at just over 35% of global production in 2011.

Of significance is the use of maize in China for other industrial applications. The rapid rise in China's industrial use of corn was encouraged by government incentives and policies, as well as significant domestic demand for corn-based chemicals and additives (Gale *et al*. 2009). The primary non-energy, industrial uses of corn include: pharmaceuticals, cleaning solutions, paints, plastics, adhesives, paper products, and textiles (Paasche 2012).

Of all cereal crops, maize is the largest component of global trade, accounting for nearly 75% of all traded cereals in recent years (ERS 2014). Consequently, there are considerable spatial diversities in terms of both production and consumption, as shown in Fig. 2. Much of the maize trade is related to animal feed, with smaller percentages intended for industrial use and food consumption.

Table 3. Global Production and Utilization (in MMT) of Maize in 2011

Production			Top Consumptive End-Uses					
Top 10 Producers	**Production**	**% of Global Total**	**Country**	**Food**	**Country**	**Feed**	**Country**	**Biofuel**
USA	313.9	35.4%	Mexico	13.8	China	129.0	USA	127.0
China	192.9	21.8%	China	10.3	USA	115.7	EU-28	5.0
Brazil	55.7	6.3%	Indonesia	8.3	Brazil	35.9	China	3.9
Argentina	23.8	2.7%	India	8.0	Ukraine	12.8	Canada	2.7
Ukraine	22.8	2.6%	South Africa	5.2	Japan	11.2	Australia	0.7
India	21.8	2.5%	Nigeria	5.1	Italy	10.6	India	0.3
Mexico	17.6	2.0%	Egypt	5.0	Mexico	9.6	Uruguay	0.2
Indonesia	17.6	2.0%	Brazil	4.8	Romania	8.5	Paraguay	0.2
France	15.9	1.8%	USA	3.9	Canada	8.2	Ukraine	0.2
Romania	11.7	1.3%	Ethiopia	3.8	Egypt	7.4	Kazakhstan	0.1
Author's calculations were based on data from FAOSTAT 2014 and OECD, 2014.								

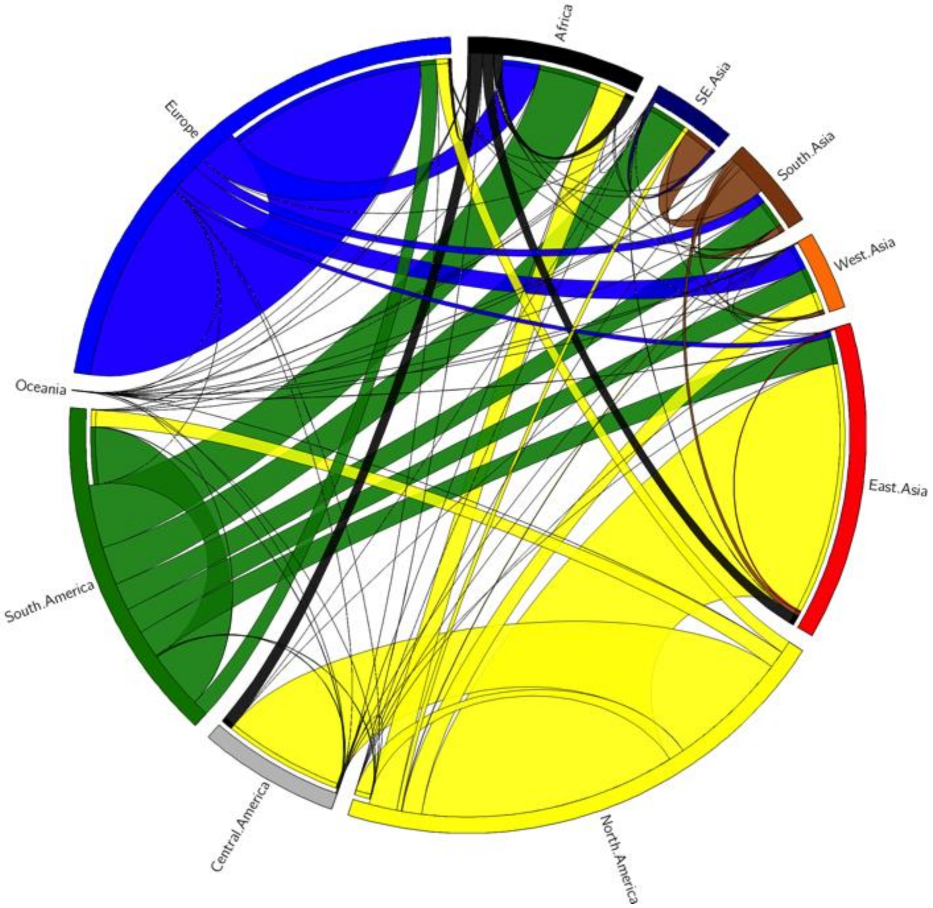

Fig. 2. The circular flow plot visualizes the global flow of maize on a regional basis. The imports and exports of maize are represented by the various segments within the circle, with the direction of the flow denoted by the color of the origin region, as well as a gap between the flow and the destination region. Flows are depicted to scale. However, as flow widths are nonlinearly adapted to the curvature of the circle, quantities are based off of the beginning/end of the flow segment, with larger bands representing a larger trade of maize.

Palm oil

Palm oil was the most produced vegetable oil in 2011. As presented in Table 4, close to 90% of global production of palm oil occurred in Indonesia and Malaysia. Commonly used as cooking oil across Asia, industrial uses of palm oil are increasing. It is commonly accepted that half of all packaged products contain palm oil. Industrial purposes of palm oil include soap, lubricants, greases, candles, cosmetics, and pharmaceuticals. However, the utilization of palm oil for energy, specifically as a feedstock for biodiesel, has increased rapidly in recent years because of the competitive price of palm oil in comparison to other vegetable oils. The EU biofuels sector increased the use of palm oil by 365% from 2006 to 2012, as a result of government mandates that stimulated the increased production of biofuels (Gerasimchuk and Koh 2013). It was reported that palm oil use in EU biodiesel production increased to a record of 1.69 MMT in 2012 (McFerron 2013).

Table 4. Global Production and Utilization (in MMT) of Palm Oil in 2011

Production			**Top Consumptive End-Uses**					
Top 10 Producers	**Produc-tion**	**% of Global Total**	**Country**	**Food**	**Country**	**Bio-fuel**	**Country**	**Other Industrial**
Indonesia	23.1	47.6%	China	3.1	Nether-lands	0.5	India	4.2
Malaysia	18.9	39.0%	India	1.8	Germany	0.3	Indonesia	3.6
Thailand	1.5	3.2%	Pakistan	1.3	Italy	0.2	China	3.6
Colombia	0.9	1.9%	Indonesia	1.1	Finland	0.2	Thailand	1.1
Nigeria	0.9	1.9%	Nigeria	0.9	Spain	0.2	USA	1.0
Côte d'Ivoire	0.4	0.8%	Colombia	0.5	France	0.1	Nigeria	0.9
Cameroon	0.4	0.7%	Bangladesh	0.4	Poland	0.1	Pakistan	0.7
Honduras	0.3	0.7%	Mexico	0.3	Portugal	0.1	Russia	0.6
Ecuador	0.3	0.6%	Brazil	0.3	Austria	0.1	Germany	0.6
Brazil	0.3	0.6%	Turkey	0.3	Belgium	0.1	Italy	0.6

Palm oil use for biofuel is limited in geographic scope to the EU, and quantities shown are for 2012. Author calculations are based on data from Gerasimchuk and Koh 2013 and FAOSTAT 2014.

The use of palm oil for industrial purposes has received increased attention from NGO's and policy makers because of the potential ecological system impacts in sensitive areas of South East Asia. As a way to depict the trade flow dependence of the west on palm oil from South East Asia, Fig. 3 shows the global flow of palm oil. The increasing reliance on palm oil from non-producing regions places mounting land-use stress on South East Asia, which is the primary supplier for global palm oil demand.

Soybeans

In 1765, the first soybeans were planted in North America. Today, more U.S cropland is used for soybeans than is used for wheat (Brown 2009). About 10% of soy is directly consumed as food, including tofu, meat substitutes, and soy sauce. Nearly one fifth is extracted as oil, and about 70% is used as soybean meal for livestock and poultry. South America is rapidly becoming the major soy-producing region; however, costs to get the products to market are exaggerated because of the transportation infrastructure needs in Brazil and Argentina (Schnepf *et al*. 2001).

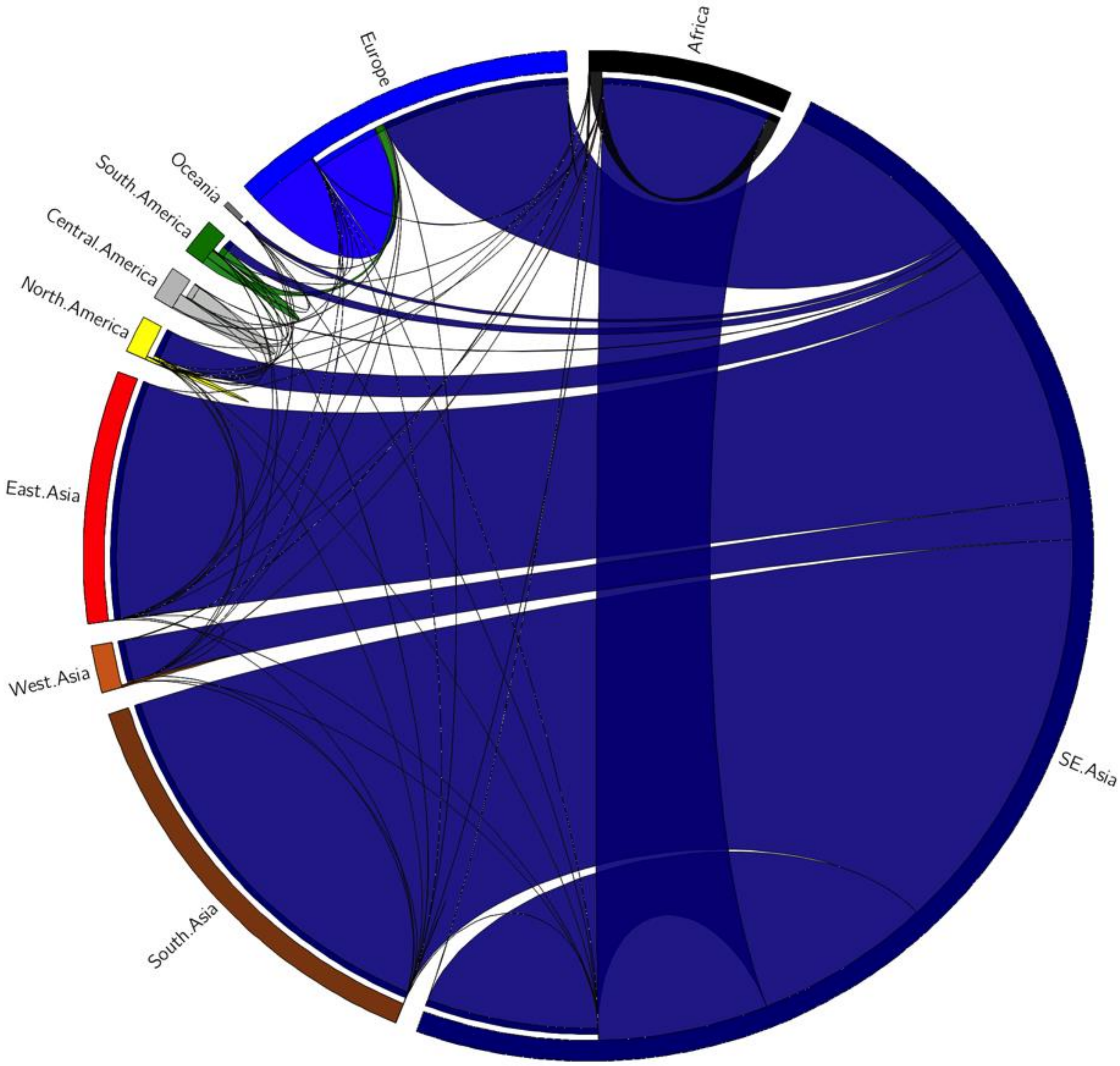

Fig. 3. Global flow of palm oil on a regional basis. The flow widths are nonlinearly adapted to the curvature of the circle. Quantities are based off of the beginning/end of the flow segment, with larger bands representing a larger trade of palm oil.

The demand for soybean as a biodiesel feedstock continues to increase, especially in the EU. As shown in Table 5, the EU was the world's largest consumer of vegetable oil for biodiesel consumption in 2011 at nearly 8.5 MMT. After rapeseed oil, soybean oil is the most utilized vegetable oil in the EU for biodiesel production. In addition to biodiesel, soybeans can also be processed into other industrial products, including solvents, inks, and plastics.

Table 5. Global Production and Utilization (in MMT) of Soybeans in 2011

Production			Top Consumptive End-Uses					
Top 10 Producers	**Produc-tion**	**% of Global Total**	**Country**	**Feed**	**Country**	**Biofuel**	**Country**	**Other Industrial**
USA	84.2	32.1%	China	6.0	EU-28	8.4	China	8.0
Brazil	74.8	28.6%	USA	2.2	Argentina	2.3	Brazil	2.9
Argentina	48.9	18.7%	Mexico	1.0	USA	2.2	Argentina	2.3
China	14.5	5.5%	Russian	0.8	Brazil	2.1	India	1.0
India	12.2	4.7%	Ukraine	0.7	Indonesia	1.5	USA	0.4
Paraguay	8.3	3.2%	Brazil	0.6	Thailand	0.7	Mexico	0.3
Canada	4.2	1.6%	Canada	0.3	Colombia	0.5	Egypt	0.3
Ukraine	2.3	0.9%	Belgium	0.3	India	0.1	Thailand	0.3
Bolivia	1.9	0.7%	Paraguay	0.3	Philippines	0.1	Peru	0.3
Uruguay	1.8	0.7%	Viet Nam	0.2	Australia	0.1	Portugal	0.2

Given commercially sensitive data, biofuel use refers to the total quantity of vegetable oils used to produce biodiesel in 2011. Author's calculations were based on data from FAOSTAT 2014 and OECD 2014.

Enhancing Bio-based LCA Methodologies

Embedded resources within the spatial flows of the bioeconomy

There have been requests for a fundamental reassessment of agricultural production and the natural resources that it depends upon (Sachs *et al*. 2010, Slade *et al*. 2011). With the ongoing emergence of a bio-based economy, greater focus is necessary in regards to the requirements of biological feedstock production. A Life Cycle Assessment (LCA) modeling approach allows for an in-depth analysis of each stage of a product, including the extraction of resources, the manufacturing and distribution phases, consumer use, and post-consumer use. Generally, multiple midpoint impact categories are evaluated, such as, ozone depletion, global warming, acidification, eutrophication, photochemical oxidation, ecotoxicity, multiple human health impacts, fossil fuel depletion, land use, and water use. A literature review of 44 LCA studies indicated that one MT of bio-based material saves between one and four MT of carbon dioxide equivalents (CO_2e) of greenhouse gases, while reducing 21 to 89 gigajoules (GJ) of primary energy consumption (Weiss *et al*. 2012). However, these findings also showed that the bio-based materials have the potential to increase eutrophication and stratospheric ozone depletion. The findings were inconclusive in regards to the acidification and photochemical ozone formation. A common association among bio-based materials was the deleterious impacts caused by fertilizer and pesticide application during the agricultural production phase.

Among biofuels and bioenergy, there are a wide array of methodologies used to estimate the LCA impacts, mainly because of the variation in the selection of system boundaries, allocation procedures, and inclusion of land-use change effects (Cherubini and Strømman 2011). The entire chain of operations, from the growing of the feedstock to its combustion, for some biomass systems, can be close to carbon neutral. For instance, net GHG emissions from the generation of a unit of electricity from bioenergy have been shown to be 5 to 10% of those from fossil fuel-based electricity generation (Cherubini *et al*. 2009). However, when considering a life cycle perspective, studies have also shown that many bioenergy systems, in comparison to fossil fuel reference systems, lead to increased environmental impacts (*e.g.*, acidification, eutrophication), notably from the use of nitrogen-based fertilizers (Kim and Dale 2008; Luo *et al*. 2009).

Although the utilization of LCAs is growing, through the expanded use by both government and industry as part of efficiency and institutional purchasing decisions, increased data (life cycle inventory) and enhanced modeling approaches are warranted. We briefly discuss two such issues: 1) Spatial LCA and, 2) Dynamic GHG accounting within LCAs.

Spatial LCAs

Table 6 displays the embedded fertilizer and water of the aforementioned four key bioeconomy feedstock crops, plus cotton, because of its significant role in the global marketplace for textile manufacturing. This information provides a comparison of the water and fertilizer impacts associated with different industrial bio-based crops at the global level; however, it does not address the importance of spatial variability.

Table 6. Embedded Resources within the Flows of Key Bioeconomy Crops, 2011

				Fertilizer Embedded in Export			**Embedded H_2O in Exports**	
	Export (MMT)	**Total Production (MMT)**	**Export % of Total Production**	**N (Tonnes)**	**P_2O_5 (Tonnes)**	**K_2O (Tonnes)**	**Green Water (m^3)**	**Blue Water (m3)**
COTTON	10.9	25.9	42%	1,748,249	706,265	492,909	8.9E+10	3.2E+10
MAIZE	115.3	887.9	13%	1,898,031	721,179	564,799	1.1E+11	6.8E+09
PALM OIL	41.3	49.3	84%	859,217	313,827	1,673,106	2.1E+11	1.9E+07
SOYBEANS	138.2	261.9	53%	218,306	1,635,033	1,669,151	2.9E+11	6.0E+09
SUGAR	33.0	171.1	19%	526,292	194,936	506,836	4.7E+10	4.9E+09

Production and export data was retrieved from the FAOSTAT (2014) database. Embedded fertilizer was calculated based on the data retrieved from the International Fertilizer Industry Association (IFA)(Heffer 2013). Embedded water was calculated from data on the water requirements of crop production from the Water Footprint Network (WFN)(Mekonnen and Hoekstra 2010).

Enhanced understanding of the water and fertilizer requirements of a crop provides insight into the overall impact of producing that crop, and ultimately its selection as a feedstock or replacement feedstock in the manufacturing of a product or energy source. Important in this discussion is the application of Spatial LCAs, which would allow for the identification and incorporation within the life cycle inventories of the specific geography/geographies of the acquired resources. For instance, soybeans produced in different regions of the world require varying degrees of fertilizer use, given the fertility of the native soil. In Argentina, 121 MT of soybeans are produced per MT of fertilizer used (N+P+K), while in China just 19 MT of soybeans are produced per MT of fertilizer used (Heffer 2013; FAOSTAT 2014). In addition to varying nutrient requirements, water requirements also vary depending on climate and geography. Cotton lint produced in varying locales can have vastly different water requirements for production. For instance, China requires 3,591 m^3 of green water and 615 m^3 of blue water per MT of cotton lint produced, while India requires 16,182 m^3 of green water and 4,654m^3 of blue water per MT of cotton lint produced. Thus, the LCA for a bio-based product derived from the same biological feedstock could have vastly different impacts depending upon where the feedstock crop was produced. Greater spatial life cycle inventory and life cycle assessment research in regards to the specificity of biological resource production will help to enhance the LCAs of bio-based energy and materials within the global bioeconomy. Geyer *et al*. (2010) proposed coupling GIS and LCA for biodiversity assessment of land use and biofuels in the U.S. In their 2013 study of biofuels, they identified a wide variance in direct land use impacts for biomass-based pathways ranging from $5m^2$/100 km to $100m^2$/100 km (*i.e.*, direct land use impacts expressed in m^2/100 km driven) (Geyer *et al*. 2013).

Dynamic GHG accounting in LCAs

Life cycle assessment is one tool for analyzing the environmental impacts of biofuel and biomaterial production and use. While an LCA has particular strengths, which include accounting for GHG emissions, it is limited in calculating environmental impacts and GHG emissions over a period of time (Reap *et al*. 2008). Thus, there is growing concern in regards to the lack of consideration of temporal aspects in both LCAs and carbon footprint analyses (Levasseur *et al*. 2012).

In a typical LCA study, any emissions that have occurred in the past, or are predicted to occur in the future, are considered to occur at “year zero,” and persist in that environment for a given time horizon. However, in reality, the emissions from the creation, use, and disposal of a product occur over many years. Therefore, in neglecting the timing of emissions, the environmental impacts of a given product over the stipulated time horizon are often distorted, especially for long-lived products or projects (Kendall 2012).

A dynamic LCA approach utilizes a dynamic inventory, which details emissions at every given time-step, as well as dynamic characterization factors to determine the impacts of emissions at each time-step (Levasseur *et al*. 2010). In regards to biofuel production, the U.S. EPA published an LCA that accounted for the direct and indirect land use change (LUC) emissions that resulted from the production of renewable biomass (EPA 2009). Yet the time horizon of LUC emissions varies considerably depending upon the fossil fuel and biofuel life cycles (O’Hare *et al*. 2009). Emissions from LUC are significant in the first year, attributable to the clearing of vegetation. However, after the first year, LUC emissions drop below the direct emissions of fossil fuel, because of the residual vegetation degradation and sacrificed sequestration potential of the natural land (Levasseur *et al*. 2010). Resultantly, the GHG emissions per unit energy are higher for biofuel than for the displaced fossil fuel for the first year, given the GHG emissions that result from clearing the land. Yet for subsequent years, life-cycle GHG emissions are consequently lower for biofuels than for traditional petroleum fuels. Thus, the time horizon of an LCA has a crucial impact on the estimated benefits of the project (Korhonen *et al*. 2002).

In the forestry sector, the production of cellulosic biofuels oftentimes does not occur in one year, but rather could occur over as many as 50 years, depending on the biomass growth cycle (Daystar *et al*. 2014). Longer rotations mean that feedstocks will absorb more CO_2 throughout the years as opposed to short rotation feedstocks, which are usually harvested following one to three years of growth. The absorption, and subsequent (negative) emissions, can be distorted when they are summed and assumed to occur solely in the year that the biofuel was produced and combusted (Kendall *et al*. 2009). The consideration of biogenic carbon and the timing of GHG emissions with consistency in regards to the emerging bioeconomy is an area that requires further exploration.

CONCLUSIONS

1. The emerging bioeconomy must be understood within the larger context of ongoing economic (GPD growth and increasing consumption), societal (population growth), and technological growth (emerging markets require increasing connectivity and equal standards of living). A sustainable systems analysis of the bioeconomy is needed to fully explore the inter-sectoral linkages of the bioeconomy.
2. Quantification of the global flows of agricultural and forestry resources allows for a greater specificity when conducting LCAs, thereby addressing gaps and allowing for greater quantification of the risks. Further research on the spatial nature of the bioeconomy can provide insight into optimizing the production of bio-based feedstocks. Such work should be coupled into a systems framework, whereby one can analyze how impacts in other sectors, *i.e*., an increase in chemical production, could impact that of another sector, *i.e*., food and feed production.
3. With improvements in accounting of feedstock production, academia, industries, and governments will be in a better position to address the multi-dimensional feedbacks and synergies of the bioeconomy, as well as predict potential areas of risk and those that may prosper from future production increases.
4. Future demands of the bioeconomy have the potential to create new emergent markets and shipment hubs, thereby altering trading patterns (maritime shipping lanes) as emergent bio-based feedstock producers are connected with industrialized nations and/or intermediate processing hubs.

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