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INNOVATION DIFFUSION ANALYSIS FOR BIOFUELS AND BIOCHEMICALS

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OBJECTIVE

As multi-national firms and governments are increasing the demand for biofuels and biochemicals through policies and incentives the implications of the adoption of these emerging technologies is underexplored. This research examines the role of sustainability as explored through a traditional view and a Natural Resource Based View and its implications for global supply chain management.

Keywords: resource value; sustainability; bioeconomy; biofuels, biochemicals, sustainable supply chain; resource theory; innovation

I. INTRODUCTION

The Natural-Resource-Based-View (NRBV) of the firm was proposed by Hart (Hart, 1995) and builds upon the core principles of the Resource-Based View of the firm. Hart argued that the natural environment should be included as a part of a sustainable (in terms of economic rents) business strategy, proposing that firms should consider three additional strategic capabilities: (1) pollution prevention, (2) product stewardship and (3) sustainable development. These capabilities, which form part of the firm's natural environment strategy, are linked to competitive advantage through the parallel concepts of lower costs, pre-empting competitors, or future strategic position. Strategy and competitive advantage will be rooted to a large extent by capabilities that facilitate environmentally sustainable economic activity.

Hart (1995) argued that the two key tests for a natural resource to underlie advantage are that it is rare and non-imitable, achieved via characteristics of causal ambiguity, social complexity and being firm-specific. He also provides a cogent framework for evaluating the driving force, key resources, and competitive advantages for different forms of natural resource solutions.

Bioenergy and associated biochemicals as a technology has many complex aspects. Besides providing tangible benefits that align with Hart's context of pollution prevention, stewardship, and sustainable development, there are other technical and practical issues that may yet limit the diffusion of this technology into the supply chain. In this paper, we explore critical emerging technologies, bioenergy and biochemical both of which are derived from biorefining, in the research model of diffusion of innovation first proposed by Rogers and Shoemaker (1971), but using the lens of the NRBV to evaluate benefits. The emergent bioeconomy is an economy based on biomass as the raw material (or feedstock) for transportation fuels, electricity, heat, chemicals, plastics and other materials, and is viewed as a means of addressing security, economic development, environmental protection, supply chain reliability, and increased demand for "green" products. The emergence of this technology is accompanied by a number of different supply market challenges, regulatory issues, supply chain risks, and limitations that are worthy of further exploration.

In an effort to better portray and frame these issues, we build on the framework established by the NRBV to explore the opportunities, risks, and challenges that exist for effective adoption of this technology. We seek to evaluate the potential growth of bio-based feedstocks as a major innovative technology that will drive change in the industry, using an approach for diffusion of innovation first identified in a seminal work by Rogers and Shoemaker (1971).

a. Theoretical Framework

Research on diffusion of innovation has relied on several different frameworks to explain different patterns. Von Hippel et al. (2012) identified innovations as being one of two types: consumer-active or manufacturer-active. Consumer-active innovations rely on the customer as a major source of innovation ideas. Conversely, manufacturer-active innovations "push" a technology onto consumers without determining the specific need. Von Hippel has shown that manufacturer-active innovations are less likely to be adopted and diffuse in a given market than customer-active innovations. Other research suggests that the ability of a user to suggest the ultimate form of innovation to the producer will positively influence how easily it is developed and accepted in the market (Abernathy and Utterback, 1978). Rates of diffusion are also affected by factors such as competitive forces and corporate strategic objectives.

Two other widely cited studies of diffusion are those of Mansfield (1968) and Rogers and Shoemaker (1971). The set of studies by Mansfield is based on the proposition that the probability that a firm will introduce a new technique is an increasing function of the proportion of firms already using it and the profitability of doing so, but a decreasing function of the size of the investment required. Mansfield studied twelve innovations and found that the rate of imitation tended to be faster for innovations that were more profitable and required relatively smaller investments.

Mansfield's basic premise that technologies diffuse slowly due to high costs and relatively low payback makes sense. However, this model does not account for the fact that bio-based energy is not just an expensive piece of technology that is slow to gain market share. Bio-based energy offers advantages that may be difficult to measure using standard Return on Investment (ROI) measures, and which are more likely to be able to be measured through the lens of the NRBV of the firm. While simple payback criteria may be appropriate for investing in an industrial robot, the decision to invest in a bio-based energy solution is not so straightforward.

In this regard, Rogers and Shoemaker (1971) propose a model of diffusion that offers greater insights into the complex phenomenon of bio-based energy. The authors treat diffusion as a special type of communication. Diffusion is defined as the process by which innovations spread to the members of a social system. Briefly, Rogers and Shoemaker propose five attributes of innovations that affect their rate of adoption: 1) relative advantage, 2) compatibility, 3) complexity, 4) trialability, and 5) observability. In assessing attributes of the bio-based economy in each of these categories, a pattern of decision-making emerges that provides insights into the technology's relatively slow rate of diffusion, and also helps to predict what the future may bring in terms of the technology life cycle of biotechnology and its adoption into industrial and consumer supply chains.

With projections of global population rising from 6 to 9 billion, and the global middle class expected to increase from 1 to 4 billion by 2030, governments and industry alike have been seeking out ways to address resource consumption and environmental impacts of the products produced and used in society. We begin by tracing the growth of the biofuel technology as an element of pollution prevention, discussing specific attributes. Next, we assess the attributes of biotechnology for a specific industry (chemicals), and evaluate the factors that will lead to the diffusion of this technology relative to current petroleum-based solutions. We perform this evaluation by exploring the Rogers and Shoemaker's five attributes of innovation that impact diffusion. This includes exploring the "traditional" view of the technology using conventional ROI approaches as well as how organizations are adopting the technology using a new and emerging sustainable view of the firm aligned with the NRBV perspective. We provide an overall assessment of the critical issues that will determine how sustainable development technology will grow the bio-based economy. Finally, we conclude by presenting pathways to minimize the risk of adoption of biological feedstocks and technologies.

II. RELATIVE ADVANTAGE

This attribute refers to the degree to which an innovation is perceived as being better than the idea it supersedes, and is positively related to its rate of adoption. How are biofuels better, in which areas, and how to measure it? The NRBV is based on the values of pollution prevention, product stewardship, and management of upstream resources and suppliers (Priem and Swink, 2012). In this context, we explore if and how energy and products using biological resources compare to traditional petroleum based counterparts, including which areas, and how to measure it?

As background, we explain why biological resources will play an even greater role in supply chains. The most well known industrial utilization of biological feedstocks is for energy production. The trend to use biological resources for energy is expected to continue. For example, in the United States, Congress established a Renewable Fuel Standard (RFS) under the Energy Policy Act of 2005, which mandated that a minimum of 4 billion gallons of biofuels be used in 2006. With the addition of the new RFS2 legislation, annual biofuel production rises to 36 billion gallons by 2022, primarily from ethanol, biodiesel and other advanced biofuels (e.g. cellulosic biofuels). Global liquid fuel demand is forecast (British Petroleum 2013) to reach 102.4 million barrels per day (mmbpd) in 2030 and biofuels production is expected to reach 6.7 mmbpd by

2030, up from 1.8 mmbpd in 2010. The US and Brazil will continue to dominate biofuel production with 76% of total output in 2010, but falling to 68% in 2030 as output from Asia-Pacific begins to rise.

In addition to food and energy production, biological resources are increasingly being utilized for a growing manufacturing industry. A variety of factors are driving growth in market demand. First, petroleum prices are on a long-term upward trajectory, in part due to the increasing difficulty of extraction and transportation of crude oil. Around the world, over $400B worth of conventional manufacturing products are produced each year using biomass. This includes 12 billion pounds of biomass per year used in the United States for bio-based products (Informa Economics, 2006). Aided by the stabilization in glycerin prices, the biochemical sector has achieved a market value of $3.6 billion in 2011. By 2021, SBI Energy forecasts that the global bio-based chemicals market will have increased to $12.2 billion, accounting for 25.4 billion pounds of bio-based chemical production at the end of the decade (SBI Energy, 2012).

Chemical Sector	2005		2010		2025	
	TOTAL	Bio-based	TOTAL	Bio-based	TOTAL	Bio-based
Commodity	475	0.9	550	5-11	857	50-86
Specialty	375	5	435	87-110	679	300-340
Fine	100	15	125	25-32	195	88-98
Polymer	250	0.3	290	15-30	452	45-90
Total	1,200	21.2	1,400	132-183	2,183	483-614

Table #1: The expansion of the biological chemical sector globally. *Sources: USDA, (2008). Billions U.S. Dollars. Note: Pharmaceuticals not included.*

a. Economic Advantages

Between 2000 and 2010, the average cost of bringing a new oil well to production doubled (Dobbs et al., 2011). For chemicals dependent on crude oil-based feedstocks, supplies have been squeezed, thereby leading to an increase in price. As such, interest in biological feedstocks has significantly increased within the last decade. While non-food, bio-based materials like wood waste, corn stover, rice straw, and switchgrass offer the promise of lower cost feedstocks, inputs of land and water still must be considered. The effect of not leaving these materials in the field on soil conservation is a further consideration.

Particularly for non-food feedstocks, the cost of distribution to a processing facility is often the significant driver in the overall economics of bio-based feedstocks to chemicals and fuels. Biobased feedstocks usually have low bulk densities and relatively low energy densities. What is more, they often contain significant amounts of moisture. These factors lead to high distribution costs. Often scale and siting of processing facilities are limited by just how much feedstock can be brought to processing facilities economically. For grain and cellulosic ethanol facilities, the maximum economic distance that feedstock can be brought for processing has been estimated at between 50 and 75 miles (Khosla, 2012).

Volatility for biobased feedstocks has been observed, especially at times of extreme weather events (e.g., droughts, hail storms, and floods). Political unrest and labor disruptions can also influence the supply (and thereby the price) of biobased feedstocks.

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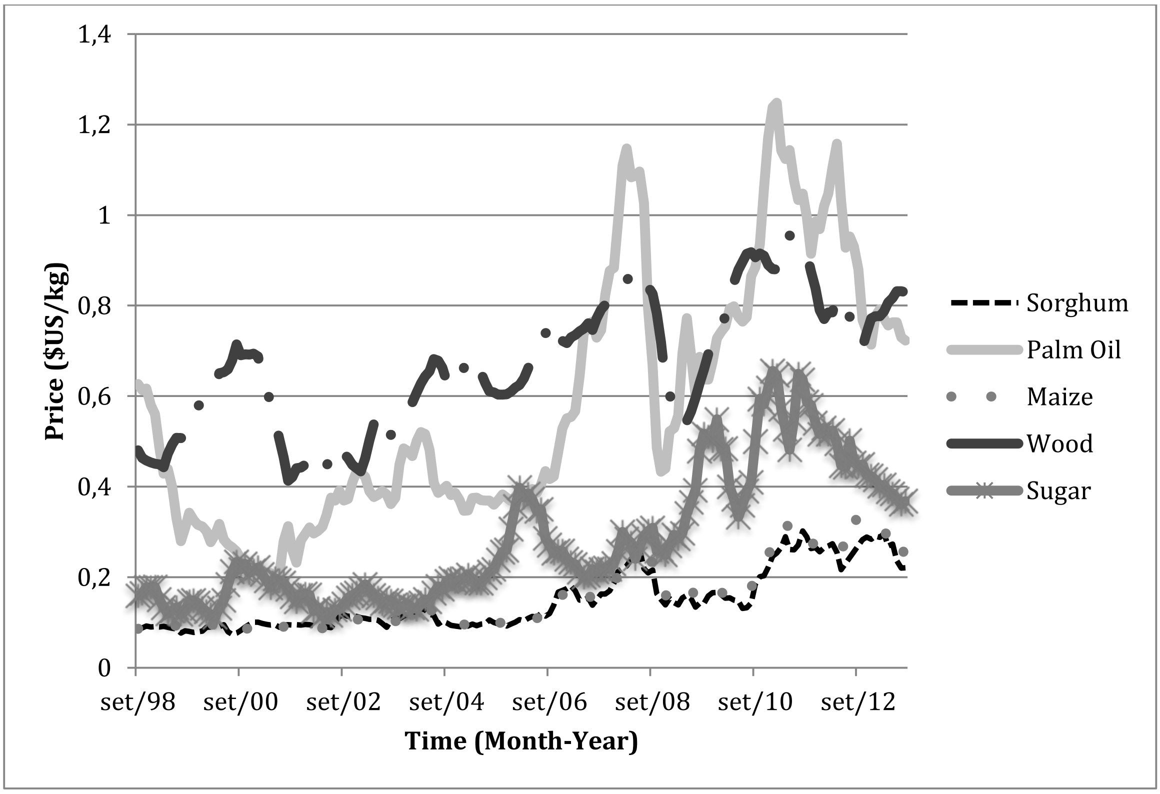

Figure #1: Historical Prices of Food and Non-Food Biological. (Source: Index Mundi, 2013)

The prices of fossil-based feedstocks have been volatile as well. Economic growth, weather, and geopolitical risks are just a few factors that historically contribute to oil price volatility (Bohi & Toman, 1996; EIA, 2013).

The use of hydraulic fracturing and directional drilling techniques to enable economic production of natural gas trapped in shale formations has helped ‘decouple’ the price of natural gas from that of crude oil, leading to lower and less volatile natural gas prices. Indeed, in the United States, natural gas-based feedstocks for fertilizers and certain fuels and chemicals (notably, ethylene chain derivatives like polyethylene and ethylene glycol) should have a significant cost advantage versus naphtha and many bio-based feedstocks for some time.

Without considering environmental costs like greenhouse-gas (GHG) footprint and other externalities like water usage, for a given end product the price spread between the bio-based feedstock and the petroleum feedstock is the critical driver in the assessing the competitiveness of a feedstock. By their nature bio-based feedstocks have higher oxygen content, and thus lower energy density, than petroleum. As such, chemicals made from bio-based feedstocks often require more processing steps than those made from petroleum. While technology, efficiencies, and co-product values can mitigate the costs associated with the additional processing steps, the value of the bio-based feedstock relative to petroleum is critical.

As presented in Figure #2, Gevo's analysis of the costs associated with a bio-based feedstock (i.e., sugar) for the production of isobutanol helps illustrate this point (Gevo, 2011). Isobutanol has a fuel value of 33 MJ/kg, about 81% that of a common petrochemical feedstock naphtha (44.9 MJ/kg). At a sugar value of $0.30/lb., and a 25% yield of sugar to product, the cost associated with the sugar in bioisobutanol is $1.15/gal. Iso-butanol derived from naphtha via propylene would have the same feedstock cost of $1.15/gal when the price of naphtha is $1000/MT.

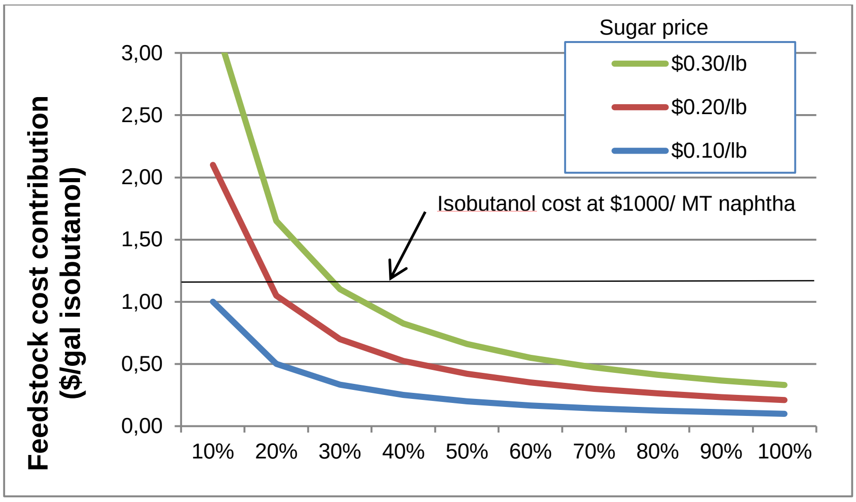

Figure #2: Feedstock Cost Contribution for Isobutanol. (Source: Adapted from Gevo, 2011)

This analysis only considers the gross raw material costs. Most often, however, the value of co-products associated with a given feedstock must be considered. In corn ethanol production the value of co-products like Dried Distillers Grains with Solubles (DDGS) has a considerable influence on process economics. In sugarcane-based and cellulosic ethanol production, the value of electricity that can be generated from solid residues can be a significant factor in the economic viability of a facility. Similarly, when naphtha is processed (i.e., 'cracked') for chemicals production, several petrochemical building blocks are produced, principally ethylene, propylene, mixed C4s, benzene, toluene and xylene. Propylene, which can be used for isobutanol production, is typically 15% of the mass of the incoming naphtha. The prices of the other co-products are therefore important in determining the net cost of the naphtha raw material.

b. Environmental Advantages

The transition to the bio-economy is strongly influenced by the drive towards environmental sustainability and the increasing cost of developing crude oil reserves and extracting crude oil. The issuance of Presidential Executive Order 13514 (White House, 2009) and the National Bioeconomy Blueprint (White House, 2012) in part helps move the nation toward a clean energy future. Individual firms like Procter & Gamble, Unilever, Coca-Cola, and DuPont are among many companies that are investing and marketing the utilization of biological feedstocks and bio-based products as substitutes to traditional petroleum based resources.

It is anticipated that the bioeconomy transition will provide many environmental advantages. Bang et al. (2009) estimates that by 2030 the use of biofuels and chemicals could prevent between 490 and 1,790 million tonnes of carbon dioxide from reaching the atmosphere every year. When utilized in place of fossil fuels, sugarcane-based and cellulosic ethanol can reduce GHG emissions by upwards of 75%.

	Freshwater Used per Gallon Produced (gal/gal)	Gallons Produced per Acre (gal/acre/yr)
Petroleum Gasoline	2.6 – 6.6	--
Soybean Biodiesel	1.0	52-59
Thermochemical Conversion	1.9	1000-4000 (est.)
Corn Ethanol (US)	3.0	401
Cellulosic Ethanol	5.9-9.8	1000-4000
Algal biofuels	0 – 964*	>9000[4]

Table # 2: Freshwater consumption comparisons. * Values vary by process. Sources: Buttazzoni, 2009; Wu et al., 2011; UNESCO, 2012; Stecker, 2012.

Summary of Findings

As presented in Table # 3, there are a variety of factors that can be considered when evaluating the relative advantages of adopting biological resources. We explore this by comparing the Traditional view versus the Natural-Resource-Based-View on various criteria including costs, environmental factors, and the supply chain. While not intended to be inclusive, it does reflect key indicators.

Relative Advantages Petroleum vs. Biological Energy/Chemicals		
	Traditional View	NRBV
Environmental criteria	Costs associated with meeting regulatory mandates	Protection of key ecosystems. Potential to meet GHG reduction targets.
Costs	Driven by supply and demand	Driven by supply, demand, GHG profile and alternative uses like food consumption
Cost fluctuations	Driven by global demand and supply, which can be subject to geopolitical events and short-term weather events like floods or rains	Driven demand and supply over the long-term, taking into account GHG profile and other environmental factors
Environmental performance	Carbon dioxide and other GHGs can be emitted at no/low cost Water resources are required for production of both petroleum-based and bio-based feedstocks; prices for such resources may not reflect long-term costs.	Emission of carbon dioxide and other GHGs has a cost, either explicit or implicit Water and other resources are priced to reflect long-term sustainability.
Resource availability long-term	Petroleum resources will be available but prices will trend upward. Biotechnology will increase crop yields to feed a growing population	Long-term concerns on carbon emissions may limit the extraction of petroleum products. Biotechnology will increase photosynthetic yields of both

		food and non-food plants while minimizing other inputs like water and fertilizers
Maturity of supply chain	Petroleum supply chain has fewer actors, and is more mature	Supply chain is more complex but there are more actors and transparency.
Regulatory frameworks / incentives	Tax incentives for oil & gas extraction, and varying levels of consumption taxes for fossil fuels	Feedstock incentives/preferences through RFS2, renewable portfolio standards (RPS) and other mandates and subsidies. Potential for carbon markets in the future.
Pollution prevention	End of pipe in Manufacturing	Greater life-cycle opportunities.
Consumer perceptions	Oligopolistic, Polluting	"Green, sustainable" technology, national security benefits

Table #3: Summary of Relative Advantages of the Bio-Economy-Traditional View vs. NRBV.

III. COMPATIBILITY

Compatibility is the degree to which an innovation is perceived as consistent with existing values, experiences, and needs of technology adopters. Compatibility is positively related to the rate of innovation adoption. Innovations in biobased materials need to be compatible with government policies such as the U.S. Renewable Fuels Standards (RFS2) legislation and California's Low Carbon Fuel Standard (LCFS). Many firms, particularly in the retail and consumer products sectors, have set corporate sustainability goals and are working to lower the GHG and environmental footprint of their products and associated supply chains. Biobased chemical innovations including bioplastics clearly need to be compatible with these goals.

Certainly prospects for growth of biobased plastics appear strong. Advancement in polymer technology has made biobased plastic alternatives to be almost perfect, in some cases exact replicates, of their petroleum-based counterparts; thus making them technically viable for widespread adoption. The main appeal of bioplastics is their lower GHG carbon footprint, in comparison with their petroleum-based analogs. Some biobased plastics and chemicals serve as functional (not compositional) equivalents to petroleum-based compounds. Some of these renewable products have natural biodegradability in the environment, which subsequently reduces impacts on both human and animal health.

Although in principle bioplastics seem to offer a viable solution for sustainable products for the future, there has been significant debate surrounding the cradle-to-gate, Life-Cycle Analysis (LCA) of renewable feedstock based polymers, and whether they are beneficial or harmful to the environment (Vink et al., 2003; Patel et al., 2005; Tabone et al., 2010).

Compatibility Petroleum vs. Biological Energy/Chemicals		
	Traditional View	NRBV
Compliance with government regulations/mandates	Sale, production and distribution comply with EPA/FDA/other regulations	Sale, production and distribution comply with EPA/FDA/other regulations, and bio-based product helps meet mandates, may be taxed less or differently or may be eligible for subsidies or credits
Consistency with customer values	The balance of price, quality and reliability brings value to customer and supplier	Customer values GHG footprint and environmental profile in addition to price, quality and reliability
Compatibility with existing distribution channels	Distributors provide service and technical assistance	Distributors need to be trained to sell the additional features like lower GHG footprint
Compatibility with existing supply chains	Existing processing and distribution infrastructure can be leveraged for bio-based materials	The economic value, GHG footprint and environmental profile need to justify adding dedicated capacity or infrastructure solely for the bio-based products.
Compatibility with existing downstream processing equipment or formulations	Even polymers and chemicals with similar molecule compositions can have different processing characteristics. Machines and formulations need to be 'tuned' to address these differences.	Bio-based compounds that serve as functional equivalents may require more complex changes to downstream processing and formulations.

Table # 4: Summary of the Compatibility of the Bio-Economy-Traditional View vs. NRBV.

IV. COMPLEXITY

Complexity is the degree to which an innovation is perceived as difficult to understand and use, and is negatively related to its rate of adoption. Perhaps the greatest challenges in substituting to bio-based products lay in three key areas. First, what is the propensity for the customer / institutional buyer to switch from a proven petroleum-based product to one with a biological feedstock? Second, what are the embedded costs associated with the transition? And finally, and likely most important, what are the costs of switching to the bio-based product?

Materials and energy derived from biomass must compete against materials and energy derived from fossil-based feedstocks. Biofuels like ethanol and biodiesel compete with gasoline and diesel as transportation fuels, and chemical intermediates and plastics derived from bio-based feedstocks have to be competitive with their fossil-based analogs. The basis of competition, however, is broader than just the 'hard' costs of feedstock prices, labor, land, and capital. Externalities like carbon footprint, energy security, supply reliability, and brand reputation must also be taken into account. Current and future government policies must be considered as well.

Many current and evolving innovative technologies are being refined or developed to allow sustainably and economically viable materials and energy from biomass, including virgin biomass from primary crops (agricultural, forestry, and marine), and from underutilized materials and land. The transition to a biobased economy requires many innovations across developed and emerging value chains. Innovations in fundamental sciences, engineering, government policies, market mechanisms, and business models are needed in agricultural practices, feedstock processing and purification, product certification and sustainability metrics.

Investment and Capital Costs

The challenge going forward is how to invest in innovations for the bio-based economy that foster an equitable allocation of value among shareholders, feedstock suppliers, biomass processors and converters, consumers, and the environment. An example of substitute products for the bio-economy includes those made from the common chemical precursor, ethylene (i.e., ethene or C2H4). Although initially produced from ethanol, ethylene has been derived from crude oil-derived naphtha or natural gas liquids for many decades. It is the molecular building block for several important plastics, textiles and chemicals. The global market for ethylene's largest volume derivative polyethylene, which is widely used in packaging and construction, exceeds 100 million tonnes per year. Over 3.5 million short tons of ethylene oxide were produced in the United States in 1997. Ethylene oxide is another ethylene derivative used for polyester, anti-freeze and industrial chemicals (Pellegrino, 2000).

The production of ethylene from bio-based ethanol is reemerging. Notably, the Brazilian multi-national company Braskem is producing polyethylene from ethylene made from sugarcane. Thus there is now commercially available packaging film from sugarcane. India Glycols is producing ethylene glycol for polyester production using ethanol that can be derived from sugar beets, sugarcane or corn. This ethylene glycol is used in the polyester for Coca Cola's bio-based PET soda bottle.

The use of ethanol made from corn, sugarcane or sugar beets in ethylene production, however, adds greater complexity to the supply chain. Crops need to be grown, harvested, and fermented; ethanol needs to be refined, transported, and converted. Extra investment is required for at least the conversion of ethanol to ethylene. Further investment may be required for ethanol production. If absolute traceability is desired, new polyethylene or ethylene oxide production capacity dedicated solely to bio-based ethylene conversion may need to be built. This new capacity likely would not have the scale efficiencies of modern, world-scale polyethylene or ethylene oxide facilities.

b. Access to Feedstock

Geography is an often-understated challenge in moving to a broad-based adaptation of biofuels and biochemicals. Fossil fuels and petrochemical feedstocks are sufficiently energy dense and there is large-scale supporting infrastructure to justify their shipment all over the world. By contrast, biomass feedstocks are less energy dense and often contain significant amounts of moisture. Therefore, it is generally more economical to process biomass close to its source. In developing the biofuel / biochemical economy, conversion and manufacturing technologies have to be appropriate for the local types of biomass feedstocks.

c. Competition for Feedstock

Biofuels and biochemicals produced from food crops must compete for feedstocks with hungry consumers. This competition should intensify in the future as the world struggles to feed a growing population by increasing crop yields in the face of climate change. The United Nations Food and Agricultural Organization (Alexandratos & Bruinsma, 2012) has estimated that between 2005 and 2050, cereals production must increase by 940 million tons, meat production must increase by 196 million tons, and oil crop production must increase by 133 million tons to satisfy projected demand for agricultural products (food, feed, fiber and biofuels). These estimates include average annual growth rates for the production of cereal and sugarcane-based biofuels of 2% and 2.6%, respectively, from 2012 levels.

The FAO projects that an additional 70 million hectares of land will be required for the increased agricultural production in 2050. While it is estimated that sufficient land will be available, the precise location of such land, and how much investment would be needed to develop it, is a significant issue, as are the unknown potential implications of weather fluctuations in regions due to the impacts of climate change.

d. Lack of clarity on how consumers value biobased products

While a fraction of the population and politicians in the United States remains polarized, or disputing of, the scientific consensus on climate change (McCright and

Dunlap, 2011; Leiserowitz et al. 2012), key business sectors in the United States and Europe are increasingly innovating to reduce dependency on fossil-fuel-based products that are associated with higher carbon dioxide emissions. The central question is just how much consumers will value biochemical derived products relative to fossil fuel based products. Just how more will consumers be willing to pay? And, how explicitly or implicitly will they value a ton of carbon dioxide or GHG reduction?

e. Uncertainty in government policies

Will consumers and voters be willing to bear the cost of subsidies or mandates to foster reduction in GHGs and the reduced environmental footprint brought by biobased products? To what level? For how long? How will disparate interests and politicians work to pass or modify legislation or regulations?

Government policies and their often time-limited or inconsistent application have, and will continue to, influenced the speed of adoption of bio-based innovations. Brazilian and U.S. government policies helped bring about the fuel ethanol industry through subsidies and mandates. The subsidies for corn and sugarcane ethanol have been removed, but some level of mandate remains. Initially generous subsidies in the United States for biodiesel products, followed by their complete removal, led to a boom (and then bust) in biodiesel markets, which was accompanied by a severe oversupply (and then some scarcity) in the market for glycerine co-product. Biodiesel markets have now stabilized as subsidies have been restored, and a robust biodiesel market is providing glycerine feedstock for bio-based chemicals like propylene glycol.

Recently, renewable fuel producers have noted that the RFS2 cellulosic ethanol mandate requires them to blend more cellulosic ethanol than is available in the market. In response, the EPA has reduced the mandated volumes to match the availability of the market. Such waivers, however, give pause to current and potential investors in cellulosic ethanol capacity (EPA, 2013).

Complexity Petroleum vs. Biological Energy/Chemicals		
	Traditional View	NRBV
Raw material sourcing and distribution	Large chemical and energy companies manage procurement of petroleum-based feedstocks	Consumers desire visibility throughout the supply chain from source of biomass to the store shelf
Processing to intermediates	Large chemical and energy companies use technology and scale for high volume, reliable supply	There will additional steps to be monitored and managed. If full traceability is desired, new (perhaps inefficient) downstream conversion capacity may be required
Inventory and final product distribution	Existing fabrication, formulation and packaging assets or partners can be used. Traditional distribution assets (trucks, railcars, ships) can be leveraged to move products.	Bio-based products may need to be processed and packaged separately from traditional products. Inventory may need to be managed separately, at least through some transition period
Product qualification	Limited resources are dedicated to help customers qualify products	More time and resources may be needed to help customers qualify bio-based products, particularly those that are not molecular equivalents

Table #5: Summary of the Complexity of the Bio-Economy-Traditional View vs. NRBV.

V. TRIALABILITY

Trialability reflects the degree to which an innovation may be tested on a limited basis. The perception of increased trialability is positively related to an innovation's rate of adoption. As discussed by Rothenberg and Zyglidopoulos (2007), most research has focused on socio-political drivers. This has included governmental pressures and policies as well as various stakeholder demands (Ashford et al., 1985; Dupuy, 1997; Van Dijekn, et al., 1999). However, we find that beyond governmental pressures, many firms are adopting bio-based technologies in part due to both private institutional pressures as well as perceived competitive advantages in marketing to consumers.

In 2012, five major firms – Nike, Procter & Gamble, Coca-Cola, Heinz, Ford – formed a pre-competitive collaborative to accelerate the development of biochemical products (P&G, 2012). In many ways this resulted from the successful trialability by each of the partner firms. One such highly visible example is Coca-Cola's launch in 2009 of biochemical PET bottles. Marketed as Coke's "PlantBottle™", over 15 billion bottles have been sold in more than 25 countries. Coke is using a PET resin containing biochemical monoethylene glycol (MEG), which comprises approximately thirty percent of the bottle (European Bioplastics, 2013). The firm has been able to market that their trailability of the PlantBottle™ in 2010 eliminated nearly 30,000 metric tons of carbon dioxide – the equivalent impact of approximately 60,000 barrels of oil (Coca-Cola, 2012).

India Glycols first produced bio-derived MEG, a key intermediate for polyester production, in 1989. MEG from India Glycols is now used to support trials of Coke's PlantBottleTM and other PET applications (e.g., fibers and packaging). India Glycols also produces other bio-ethylene oxide-based products like ethoxylates and surfactants. In 1997, Ford introduced the use of foam based on soy polyols for automotive applications. By 2010, over one million Ford vehicles contain soy foam products. The company has identified that their trialability of soy seats in over one million vehicles has reduced their environmental footprint through a reduction of petroleum oil resources by one million pounds, while concurrently curbing carbon dioxide emissions by five million pounds annually (Ford, 2008).

The United States military is another example of trialability of biological feedstocks. The U.S. Navy has created its "Great Green Fleet" program, which promises to have a demonstration Green Strike Force in local operations ready to sail by 2016. A demonstration, which included the USS Nimitz, took place in July of 2012. The ships and air fleet taking part in the Green Fleet are to be powered by either nuclear or advanced biofuels (US Navy, 2012). Similarly, the commercial aviation sector is entering into its trialability stage with Boeing announcing that commercial aviation could achieve its goal of meeting 1% of jet fuel needs from biofuels by 2015. United Airlines also recently entered into a purchase agreement for 15 million gallons of biofuels over three years at Los Angeles International Airport (Warwick 2013). Furthermore, in an effort to scale and meet the aviation sector's stated goal of carbon-neutral growth beyond 2020, and halving industry emissions by 2050 (based on 2005 levels), Airbus, Boeing and Embraer entered into a joint memorandum of understanding to accelerate the use of drop-in aviation biofuels (Airbus, 2012).

Braskem first produced certified green high-density polyethylene from sugarcane-based ethanol on a limited scale in June 2007, and, after market testing and qualifications, started commercial production of this product in 2010 (Braskem, 2013). It continues to commercialize different grades of polyethylene for packaging applications.

Trialability Petroleum vs. Biological Energy/Chemicals		
	Traditional View	NRBV
Biomass gathering	Test on local farms or forests	Test on local farms or forests to balance harvesting and water and soil conservation
Conversion technology	View the raw material, labor and capital costs associated with trials as a drag on the current business	Willingness to view the likely higher, non-optimized costs of trial(s) as a strategic investment in sustainability
Intermediate processing	Leverage existing assets to process both bio-based and petroleum-based materials	Understand the value of complete traceability vs. the use of leveraged assets and co-production of bio-based and petroleum-based products
End products for the consumer	Caution over diluting the value of brand and raising customer expectations too highly	Promote the bio-based innovation; Make consumers part of the process

Table #6: Summary of the Trialability of the Bio-Economy-Traditional View vs. NRBV.

VI. OBSERVABILITY

Observability is the degree to which the results of an innovation are visible to others. This attribute is positively related to an innovation's rate of adoption. One of the key leverage points in the emergent biofuel / biochemical economy is the role institutional buyers are playing. The most well-known and strongest actor is the Sustainability Consortium launched by Walmart (Bustillo, 2009), and which now includes over 100 of the world's largest retailers, brands and manufacturers. The consortium was co-designed and founded by the lead author of this paper and leveraged the unequal purchasing power of the major member firms to move the global supply chain to improve the environmental performance of its products with the goal of improving efficiencies, costs and reducing supply chain interruption. Walmart, other retailers, and governments are further moving towards required labeling (Golden et al., 2010) of consumer products with carbon footprint life-cycle assessments, providing further visibility to consumers that bio-based fuels are used in the production of the product.

One of the results of the consortium was the recognition of the potential for current and innovative technologies to sustainably capture economically viable materials and energy from biomass, including virgin biomass from primary crops (agricultural, forestry, and marine), as well as biomass from underutilized materials and land. However, the switch to a bio-based economy requires many innovations across the life-cycle, from fundamental sciences to applied industry applications, to policy and market mechanisms in areas ranging from agricultural practices to feedstock processing and purification to product certification and sustainability metrics. Further, there is a critical need to ensure that these innovations are pursued in the context of sustainability. For example, there has been significant emphasis placed on alleviating dependence on fossil fuel by producing fuel energy from agricultural products.

Observability of bio-based supply chains is somewhat problematic. Established supply chains develop according to societal needs, and emerging ones will need time and capital to develop. Investors will shrink from risk if there are not concrete examples in place; thus attracting capital becomes an issue. North America is largely in a fossil-based economy using crude oil and natural gas, and employing processes like distillation, cracking, treating and blending to create fuel, power, chemicals, and plastics. Basic chemicals like propylene and ethylene that go into polyethylene and other downstream products prevail on the market. Bio-based supply chains for natural rubber, detergent alcohols, and ethanol are well established. Now biorefineries and biochemical plants that use biomass feedstocks such as starch crops, agricultural waste, vegetable oils, carbon dioxide, and algae or municipal solid waste, which are converted by enzymatic fermentation, acid hydrolysis, and gasification, are beginning to emerge. These new bio-based supply chains will take significant capacity investments, be based on efficient usage of supply chain systems, and require a strong collaborative commitment from consumers.

Perhaps the best example of observability is the case of Brazil's sugar-based ethanol economy. Brazil is the second-largest producer of ethanol fuel, and its sugarcane ethanol is recognized as one of the most successful alternative fuels to date. There are no longer any light vehicles in Brazil running on pure gasoline. Brazil's ethanol fuel program uses modern equipment and cheap sugarcane as the primary feedstock, and also employs the residual cane-waste ("bagasse") to produce heat and power. The efficiency of sugar-based production of heat and power results in a very competitive price, and makes it a readily observable biofuel technology.

The observability of corporate initiatives to drive sustainable biofuel economy is everywhere – at the gas pump, in the press, and in our regulatory environment. Examples will include a new set of regulations by governments and pressures from major instirutional buyers to have manufacturers and brands quanitfy the environmental and social impacts of their products, and suppliers as well as to communicate this information to consumers via labels. To meet customer, government, and shareholder demands, businesses are coming together to pre-competively create a new "Ecosystem for the Supply Chain."

Nowhere is this better exemplified than the recent launch of the Sustainable Apparel Coalition's Higg Index, which creates a global community of practice and shared knowledge that focuses on direct measurement of supplier's performance relative to carbon footprint and environmental performance. A problem with consumer labels, however, is that many people have learned to distrust product labels that proclaim products to be "organic" or based on "biofuels." And yet, many consumer products rely on bio-based materials as core ingredients. For example, Novozymes is a major producer of biochemical enzymes, with headquarters in Copenhagen and major manufacturing sites all over the world, including North Carolina. Its products (enzymes) are used in multiple industries, including beer brewing, leather, feedstocks, detergents, consumer products, and a multitude of products that most people know by brand. The core strength of the company is to replace chemicals with biotechnology, improve efficiency, and grow the use of biofuels. Its goals are to help customers derive new customer solutions, and it has worked with large companies such as P&G, Unilever, Colgate, and others in product development and design.

Whether the economics of this approach are considered by either monetizing life-cycle emissions or direct environmental impacts (e.g., water, fertilizer, pesticide application), corn-based ethanol requires, per unit of fuel produced, significant fossil fuel and fertilizer inputs that can have significant greenhouse gas impacts generally believed to be similar or lower than current petroleum-based production (Stauffer 2007; Bang et al. 2009). This is not to suggest that producing energy from bio-based resources is not an appropriate, or ultimately sustainable, strategy. It is rather to suggest that pursuing renewable feedstocks in a way that only addresses the singular goal of reducing the use of finite resources can lead to unintended consequences; that is, even greater stress on the earth's systems. In fact, there continues to be debate in the literature about the potential net costs and benefits of bio-feedstocks as a sustainable systems solution (Fiksel, 2006; O'Shea et al., 2012).

As such, the challenge for companies going forward is to invest in biological innovations that ensure that the transition to a bio-based economy is mutually beneficial to the shareholder, economy, and the environment. While environmentally conscientious consumers and institutional buyers tend to favor biologically derived materials, it is not clear that these bio-materials are truly environmentally benign relative to their petrochemical analogs. In particular, there are four impact areas that are poorly quantified: (1) the water use and impacts associated with increased farming of a single crop, (2) land use and land cover change impacts on agriculture and food availability, (3) the economic impacts and opportunities, and (4) greenhouse gas emissions associated with both transportation and manufacture of the product.

Observability Petroleum Based Energy/Chemicals vs. Biological Energy/Chemicals		
	Traditional View	NRBV
Bio-based consumer products	Consumers won't pay premiums for organics and biofuels or believe the products will not perform as well as traditional formulations.	Consumers view themselves as part of an ecosystem and will support bio-based products as better for them and the environment. Demand or design will not make the products more expensive.
Bio-based fuel	Biofuels will not replace traditional fuels, and will remain corn-based ethanol.	Other forms of ethanol can be produced cheaply such as sugar-based ethanol economies (i.e., Brazil).
Bio-based fuel application	There are relative few applications for bio-based feedstocks other an ethanol for fuel.	Innovative bio-based enzymes are being used to replace traditional feedstocks in many consumer products that are on store-shelves.

Table #7: Summary of the Observability of the Bio-Economy-Traditional View vs. NRBV.

VII. DISCUSSIONS & CONCLUSIONS

The Natural-Resource-Based-View (NRBV) of the firm was proposed and explored utilizing the emergent bio-economy of biofuels and biochemicals. We expanded how consumers and firms acting as individual actors and as members of pre-competitive industry consortia consider the adoption of the biofuels and biochemicals.

This evaluation, including the rate of adoption of biological resources, incorporated Rogers and Shoemaker's five attributes of innovations: 1) relative advantage, 2) compatibility, 3) complexity, 4) trialability, and 5) observability. Our application of Roger and Shoemaker's technology adoption criteria was carried out using two distinct theoretical lenses: the "Traditional" view that embodies typical industry and consumer views of biofuels, and the "Natural-Resource-Based-View" of the firm promoted by Hart (1995) and others. The latter approach is based on the simple concept that businesses (markets) will be constrained by, and dependent upon, ecosystems (nature), and that organizations will need to consider the limitations and constraints of their ecosystem in creating strategy and building competitive advantage. Such an approach is forward thinking, and must consider all potential supply chain impacts and innovations that arise in the context of the broader environmentally sustainable economic activity (Hart, 1995). Our analysis here adopts this perspective in assessing the a more holistic and visionary scope of possible applications, constraints, and opportunities that arise when considering biofuels / biochemicals versus traditional fossil-fuel based activity from the NRBV strategic

Table 8 provides a summary view of these two very diverse perspectives. In terms of an overall assessment, the NRBV provides a much more positive view of biofuels/biochemicals as an alternative to non-renewable fossil fuels. In the traditional view, fossil fuels and fossil fuel derived chemicals indeed appear to be more compatible, less complex, much more familiar (and thus more trialable and observable). However, an increasingly large set of early adopters of biofuel technology in the global ecosystem are demonstrating the relative advantages of biofuels, which make them readily compatible with existing production systems and industrial supply chains. While biofuels have not yet reached a status of superior advantage when it comes to complexity and trialability for the general public and industry compared to fossil fuels, the biofuels sector is making progress. Finally, demonstrated success stories in the form of biofuel industrial supply chains are becoming more prominent, placing biofuels on par with fossil fuels based on observability in the context of the NRBV.

Table #8: Traditional View vs. Natural-Resource-Based-View of the Firm

	TRADITIONAL VIEW		NRBV VIEW OF THE FIRM	
	BIOBASED	PETROLEUM	BIOBASED	PETROLEUM
Relative Advantage	0	0	+	-
Compatibility	-	+	+	-
Complexity	-	+	0	+
Trialability	-	+	0	+
Observability	-	+	+	+

Our analysis here provides an important input into market intelligence for industries considering a foray into the biofuels / biochemicals sector. Early adopters in this case will help to set the stage, and also be able to drive regulatory mandates and competitive advantage for biofuels as the landscape continues to evolve. Biofuels / biochemicals represents not only a technology that can help drive sustainability performance, but also competitive performance and strategic advantage.

While adoption of biofuels and biochemicals presents firms with various opportunities, as with many new technologies there are risks. This is especially true of technologies dependent on earth resources, which are subjected to climate, economic and geopolitical vulnerabilities. In order to move to a bio-based economy, there remain fundamental and critical questions to producing the right biomass at scale to meet the needs for fuel and chemical supply chains while maintaining quality and price for competing demands; most notably food.

There are inherent tradeoffs in moving from petroleum to bio-based feedstocks related to land use, nitrification, and water demand. It is imperative to model the currently available approaches and technologies for agricultural production to identify the "greenest" pathways to highest yields. However, there is also a regional question of which feedstocks should be grown in what locations, by what agricultural practices, and at what scale. For example, sucrose can be effectively and efficiently derived from sugar beets and sugarcane, so the feedstock decision will be reliant on location, current yields, opportunity costs in terms of land use, and whether there are desirable co-products that are regionally relevant. It will also be necessary to consider carbon management, and sequestration, and the role of climate change uncertainty in crop selection and infrastructure for the coming decades.

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