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The Supply Risks and Resilience of Biofuels

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Abstract

Biofuels have been evaluated based on their greenhouse gas emissions, costs, and potential scale of production. Here we argue that the resilience against supply risks should be considered in addition to these previously-proposed metrics for evaluating the scalability potential of transportation biofuels[1]*. Biofuels rely on agricultural production as their key input, which is subject to various risks. A risky supply in conjunction with a highly inelastic demand for transportation fuels can cause price fluctuations, profit volatility, and quantitative shortages which imply negative consequences for biofuels firms, the biofuels industry, and consumers. Thus, it is an important issue both at the firm level as well as from a public policy point of view. We decompose biofuels feedstock risks into supply shocks (due to random events) and competing demand shocks (a function of demand for food crops which is partially unpredictable) and show that the historical yields and production of major crops used in the biofuels industry show a significant level of volatility. We compare first and second generation biofuels and then discuss various strategies for reducing the supply risks of biofuels. We relate the resilience of the biofuels supply chain to scale,*

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[1]We use the word *resilience* to refer to the low variability of an outcome variable, both in terms of the variance (capturing continuous changes around the mean) and extreme values (captured by higher moments). In our case, we focus on the resilience of key outcome metrics of the biofuels industry such as the quantity of biofuels supplied to the market and the price of processed biofuels. Resilience is a function of both the logistics network structure and the portfolio of input nodes, as will be discussed throughout the paper.

technological specifications, input and output market structure, and contractual setups. Our framework is applied to the case of biofuels; however, it provides general insights and analytical frameworks to analyze the scalability potential of other emerging technologies.

1 Introduction

Biofuels have been proposed as a candidate for fueling a sustainable transportation sector of the future (IEA (2004), Ragauskas et al. (2006)). A combination of government mandates and taxes on CO_2 emissions are increasing the contribution of biofuels to the overall fuel mix. For example, the U.S. Renewable Fuel Standard (RFS) requires the annual share of biofuels to reach 35 billion gallons per year by 2025, contributing an estimated 12% of all transportation fuels consumed in the U.S. (Annual Energy Outlook 2011). Similar mandates have already been implemented or are under consideration in other countries as well.[2]

The literature has extensively covered the aggregate impacts of switching to biofuels (e.g. McDonald et al. (2006), Banse et al. (2008), Westhoff (2010)) as well as three major limiting factors for the scalability and performance of biofuels (see for example Farrell et al. (2006) and and McKone et al. (2011), Peters and Thielmann (2008)). First, hard limits on the total supply of feedstock due to limited availability of fertile land is a major potential barrier (Rajagopal et al. (2007)), in particular for first-generation biofuels. Second, various studies have reported estimations about the life-cycle emission (LCA) impacts of biofuels (e.g. Lardon et al. (2009), Gnansounou et al. (2009), Ewing and Msangi (2009), Pimentel and Patzek (2005)). Some of these studies have concluded that first-generation biofuels may result in higher emissions than current gasoline and diesel fuels whereas second-generation biofuels will result in lower emissions (see for example Havlik et al. 2011). Finally, although first-generation biofuels are close to cost-competitive in certain regions such as Brazil and the U.S., the cost of second-generation biofuels remains a major concern (Carriquiry, Du, and Timilsina (2011)).

We argue that in addition to these three key metrics, the resilience (or riskiness) of the biofuels supply-chain is fourth metric which is important for evaluating the scalability and performance of biofuels. Shocks to the supply of biofuels feedstock can be caused by a number of factors. Shocks may affect feedstock production (e.g. due to disruptive weather events), processing capacity (e.g. due to under-investment), supply networks (e.g. the loss of transportation infrastructure), and demand from competing sectors (e.g. due to a surge in the demand for food). The shortage of ethanol supply in Brazil (2010/2011) is an important recent example of a

[2] http://www.biofuelsdigest.com/bdigest/2011/07/21/biofuels-mandates-around-the-world/

supply shock.[3]

There are multiple reasons why it is important to consider the resilience of biofuels supply chains, particularly under a scaled-up scenario. These include 1) the potential for greater relative risk as compared to fossil fuels supply; and 2) the high societal consequence from disruption due to the inelasticity of energy demand. These two features are considered in more detail in the following sections.

After describing the relevance of biofuels risks (Section 2.1), we discuss various mechanisms which affect the risk exposure of biofuels supply networks (Section 2.2). We focus our attention mostly on firm-level and industry-level perspectives but also use this foundation to discuss the societal-level perspective. Understanding firm-level incentives and feasible strategies for managing risks provides a bottom-up and micro-founded basis for developing aggregate metrics and macro-level policies.[4] In Section 3, a general model of risk and resilience is provided and determinants of risk/resilience are suggested. Finally, in Section 4, we review several risk management strategies for the case of the biofuels industry.

2 The Relevance and Structure of Biofuels Risks

Here we begin by discussing the relevance of biofuels risks and the societal cost of supply shocks. We then briefly compare the supply risks associated with biofuels to that of fossil fuels. The second half of this section discusses how risk is expected to change with the scale of production, across contractual setups and across technologies.

[3] In 2010 and 2011, the Brazilian ethanol industry was adversely affected by a low supply of financial resources due to the global financial crisis. Moreover, unfavorable weather conditions caused a poor yield of sugarcane together with an increased price of sugar in the global market. This encouraged ethanol producing units to focus more on sugar than biofuels. The total production of ethanol was reduced to 21.1 billion liters, significantly lower than 26.2 billion liters produced in 2010. In response, the Brazilian government relaxed mandatory fuel blending regulations to allow for greater gasoline in the market. In addition, approximately 5 billion liters of biofuel was imported from the United States.
http://www.economist.com/node/21542431?frsc=dg|a
http://www.ethanolproducer.com/articles/8323/by-train-by-truck-or-by-boat
http://www.businessweek.com/news/2012-03-13/brazil-ethanol-slows#p1
http://www.ft.com/cms/s/0/f1486874-775d-11e0-824c-00144feabdc0.html#axzz1vmVwbBIP

[4] A recent case provides a real-world example for why firms may be concerned with biofuels supply risks. At the end of 2011 oil refiners in the US had to pay 6.8 million dollars in penalties because they failed to maintain the required minimum amount of cellulosic biofuels. The required quantity of cellulosic biofuels was simply not available on the market due to a production shortfall.
http://www.nytimes.com/2012/01/10/business/energy-environment/companies-face-fines-for-not-using-unavailable-biofuel.html

2.1 The Relevance of Supply Risks

We first examine the magnitude of risks, in order to understand their relevance to the scalability and performance of biofuels. We then discuss the anticipated impacts on society.

2.1.1 How Risky is the Supply of Biofuels?

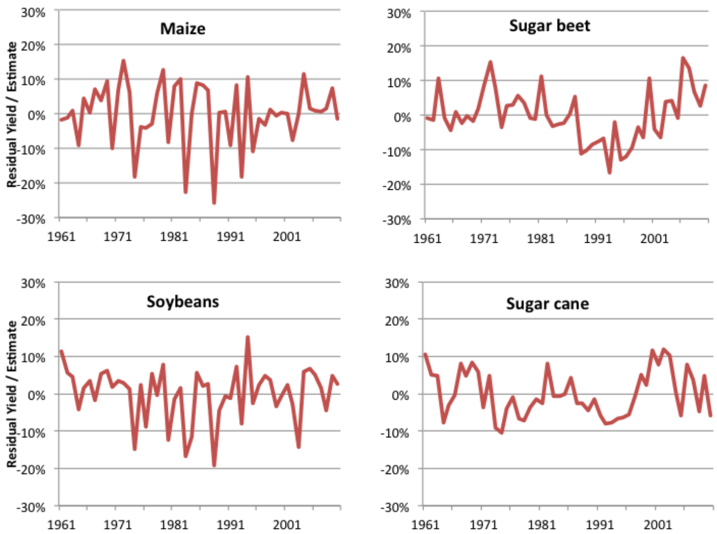
Crop yields are commonly described as random variables (Swanson and Nyankori (1979), Kucharik and Ramankutty (2005)). The realization of crop yield depends on various factors such as climate (Chen, McCarl, and Schimmelpfennig (2004), Porter and Semenov (2005), Lobell and Asner (2003)), precipitation (de Wit, Boogaard, and van Diepen (2005)), diseases (Teng, Blackie, and Close (1977)), use of fertilizers (Stewart, Dibb, Johnston, and Smyth (2005)) and (time-varying) soil quality (Kravchenkoa and Bullock (2000)). Wallach, Makowski, and Jones (2006) provide a comprehensive review of modeling risky yields.

Volatile crop price is a direct consequence of the variability in the net supply of crops to the market. However, supply variability is not the only factor leading to a volatile price. Price volatility can be caused by both demand (unexpected increases or decreases) and supply shocks, which can be partially correlated to each other. Several papers have looked into the contribution of supply and demand factors in the dynamics of food crop prices (e.g. Trostle (2008)).

In the case of biofuels and their interaction with the global fuel market, McPhail (2011) uses a Structural Vector Autoregression (SVAR) framework to decompose shocks to the biofuels market price into demand and supply shocks. The findings suggest that at the current scale biofuels feedstock shocks are manageable and do not have a significant impact on global crude oil price. However, the paper emphasizes that this is due to the small share of biofuels in the global fuel market. Once the share of biofuels in the global transportation market increases, shocks to crop yields can have a significant impact.

To provide some proxies for supply risks, we collected data on the yields of four major crops used for biofuels (corn, sugarcane, sugar beet and soybean) in the U.S. from the FAO website. Since we do not consider land use variations (which is an additional risk factor for the total supply) yield variations provide an optimistic estimation for the annual production volatility. The residuals of the time-series (Figure 1) show a volatility in the range of $[-15\%, +15\%]$ for the U.S. around the trend line, or in other words a total variation of 30% for the U.S.

Figure 1: United States Yield Residuals



2.1.2 How Costly are Biofuels Supply Shocks?

The riskiness of an input is much less of a concern, from a societal perspective, if the market for the output product has the flexibility to shift its demand between different periods or across substitute goods.[5] The U.S. transportation market does not follow this rule; a large body of literature suggests that the short-term price elasticity of gasoline demand (as a proxy for transportation fuels) is very small (see Hughes, Knittel, and Sperling (2008)). When the demand side is inelastic (a sign of not having a real substitute, at least in the short-term) small changes to the supply can cause very large swings in the equilibrium price and thus will affect consumer welfare adversely.[6]

To demonstrate the price impact of biofuels supply disruptions we use a constant-elasticity demand function ($P_G = Xq^\gamma$) for the gasoline market[7] and assume an elasticity parameter of $\gamma = -9$ which is in the range of reported results (Hughes, Knittel, and Sperling (2008)). Depending on legal mandates and engine technologies fossil-fuel (gasoline or diesel) and

[5]The opposite is true for the firm perspective. If the output market demand is highly inelastic, shocks to the input market of producers is less costly compared to an elastic market case. The reason is that in an elastic market output price reacts strongly to reduced supply and thus compensates (partially) for the reduced quantity of production.

[6]Hurricane Katrina provides a historical example of an exogenously-driven supply shock in the transportation fuels market. The hurricane damaged oil refining industry in the Gulf of Mexico, causing a reduction of operable capacity by 20%. This 20% drop in the capacity, which lasted for a few weeks, caused a historical surge in the gasoline price. The crack spreads (the difference between gasoline and crude oil price) went up from the usual 5–10% to 40%. (Lewis (2009)). Data available on the EIA website.

[7]P_G is the equilibrium price of fuels, X is the income effect factor, q is the supply of fuel to the market and γ is the elasticity parameter.

biofuels could be perfect substitutes and form an integrated market or be supplied separately and create disjointed market segments. In the case of an integrated market (in which fossil fuels and biofuels are perfect substitutes), if biofuels contribute 20% of transportation fuels and the fossil fuel sector is not flexible enough to compensate for the reduction in biofuels supply, a 15% reduction in the supply of biofuels can cause the market price of the final fuel (i.e. the mix of biofuels and fossil fuels) to move up to 30%. However, if biofuels serve a disjointed market segment (e.g. exclusively serve the E100 fuel due to engine limitations), then the same 15% negative shock to biofuels supply can cause the price of biofuels to increase by 300%.

The simple calculations in the above example elaborates the importance of scale of biofuels' contribution. If biofuels serves as a major contributor to the transportation sector, shocks to biofuels supply will be important even where there is an integrated market if the fossil fuel sector does not have enough spare capacity to compensate for the reduced biofuels supply.

2.1.3 Relative Risk of Biofuels: Biofuels versus Fossil Fuels

To quantify the magnitude of risks to biofuels supply, one can use a relative (compared to other technologies) or an absolute measure (with respect to an acceptable threshold of risk). In a relative comparison, biofuels supply risks can be compared to those of fossil fuels. The two fuels differ in the following respects:

1) The volume of refined products (including gasoline, diesel, jet fuel, and kerosene) compared to crude oil is close to one.[8] Considering the decaying quality of refined products, it is less costly to transport crude oil than to transport final fuel (given that there is enough refining capacity). However, in the case of biofuels, feedstock is much more voluminous compared to the final fuel. Thus, the input network of biofuels is not as integrated and connected as the crude oil market,[9] which implies that local supply risks have a higher order of importance for the biofuels industry.

2) The supply of crude oil comes from (exhaustible) reserves and given spare capacity on the supply side,[10] the supply rate can be adjusted (at

[8]Input and output quantities of U.S. refineries are available from the EIA website. For example, the refinery and blender net production during 2010 was 18,452 Thousand barrels per day. The net input to refiners at the same year was 17,385 Thousand barrels per day, suggesting a conversion ratio of 1.06.

[9]There are a few major quality categories for crude oil and a typical refinery can process only certain types of crude oil (e.g. light or sour crude oil). Therefore, there is some fragmentation within the global crude oil market. However, each quality segment is usually large. Moreover, refiners can switch the input crude oil type by making some costly adjustments.

[10]http://www.opec.org/opec_web/en/data_graphs/646.htm

the present time up to a maximum of 3-4 million barrels per day) to meet demand. However, the supply of biofuels depends on exogenous factors which are known only ex-post. Adjusting instantaneous supply of biofuels feedstock is more difficult than fossil fuels. Storage technology enables the supply of feedstock and/or biofuels to be adjusted to the realized demand. However, the extent of adjustment will be limited to available storage capacity and the inventory of crops.

3) Crude oil and refinery infrastructure are subject to various shocks. However, the damage from exogenous shocks can be addressed in a relatively short time.[11]

4) In the case of first-generation biofuels, the market for feedstocks is subject to random competing demand shocks from the food sector, which implies an additive risk from the supply as well as competing demand sector. Whereas, in the case of fossil fuels the refinery sector is the sole demand source for crude oil.

5) Unlike biofuels feedstock, crude oil supply is subject to strategic manipulation of the market by key suppliers, especially OPEC members. This creates advantages (stabilized prices due to price policing measures) and disadvantages (the possibility of strategic supply or price manipulation by large producers or OPEC members) for the fossil fuel sector.

To estimate the importance of each factor and understand the aggregate riskiness of each market, one needs to rely on empirical estimation. For a theoretical discussion and historical review refer to Hamilton (2003). Moreover, Kilian (2009) provides the most updated estimation of supply risks in the crude oil market using the SVAR framework. His results suggest that over time demand shocks are becoming more responsible for price volatility of crude oil and that the supply side shows smaller volatility. In particular, he shows that intentional manipulation of supply (i.e. political risks) has become less important over time.

We conclude from the estimations by Kilian (2009) that even with a relatively stable supply of fossil fuels the market prices of fuels are quite volatile. Under certain conditions, the volatility of the fuel market could be even higher than it is today if biofuels (with a risker supply technology) become an important source of supply.

[11]For example, Hurricane Katrina hit the oil production and refinery facilities in the Gulf of Mexico in late August 2005 causing a sudden 20% drop in U.S. refinery capacity. However, the refining capacity was back to the normal level by November 2005. (Capacity data from the EIA website)

2.2 Structure of Risks in the Biofuels Supply Chain

In this section we discuss how the risk profile of biofuels changes with features such as production scale, technology generation and market structure.

2.2.1 Risk and Scale

At the present state of the biofuels market, in which the main focus is on creating and expanding the market through various mandates, the importance of shocks and the impact on price and quantity volatility can be considered of second-order importance and may be overlooked by firms. Moreover, as long as the share of biofuels from total agricultural production and the contribution of biofuels to transportation fuels are both small, the volatility in the net supply of feedstock is not a primary concern from a societal perspective.

However, under a scaled scenario in which the biofuels sector contributes substantially more to the transportation fuels sector, the aggregate supply volatility may become a real challenge from a societal perspective.[12] In the absence of policy mandates, the volatility will be of first order concern to firms and the industry as a whole. On the other hand, a higher scale of production at the global level should cause various production centers (possibly based on diverse feedstocks) to emerge. This will increase the number of nodes in the supply network and improve market integration. Thus, scale can both mitigate and increase supply risk.

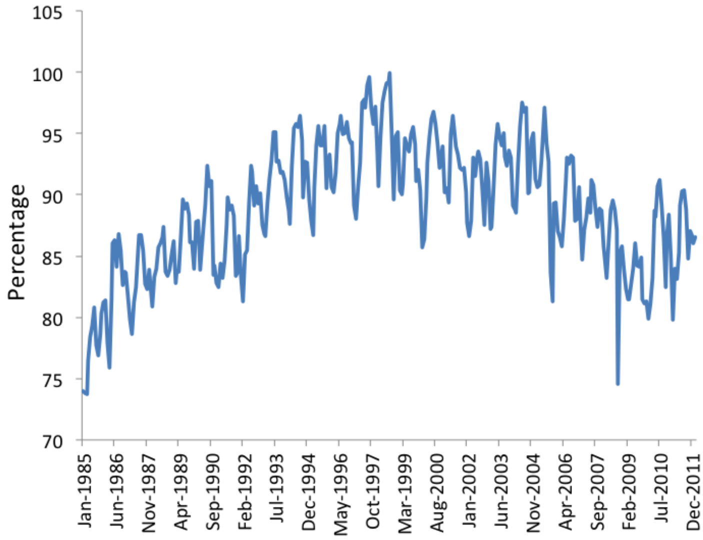
Here we outline three reasons why risks may be more relevant in a large-scale production scenario. (The first two reasons assume that engines are flexible and can be run on a variety of fuels. If engines are not flexible and require a certain quantity of biofuels to be blended with conventional fuels (or use pure biofuels, e.g. E100) the negative shock to biofuels supply will affect a large number of consumers and the first two mitigation pathways noted below will not apply.)

First, if the relative magnitude of shocks to biofuels is small compared to the total supply capacity and engines are flexible, the alternative supply technology (i.e. fossil fuels) would be able to provide a cushion through adjusting its production capacity. However, if the share of biofuels is large then the absolute value of volatility in biofuels supply would be large and can easily exceed the adjustment capacity of the fossil fuels sector. Oil refiners currently produce roughly around 90% of their maximum operable capacity (see Figure 2) and thus can increase the production in a range of

[12] A similar tension can be observed in the electricity market. The trade-off in that market is between conventional, high-emission, and stable energy sources (e.g. coal and natural gas based technologies) on one side and renewable but more volatile sources on the other side. Active research (e.g. Katzenstein, Fertig, and Apt (2010), Neuhoff (2005)) is ongoing to determine how technologies which are subject to random supply shocks (such as wind and solar) should be optimally incorporated into the national power system.

$+/-5\%$. This puts an upper limit on the ability of the oil refining sector to respond to biofuels supply shocks.

Figure 2: US Percent Utilization of Refinery Operable Capacity (Source: EIA)



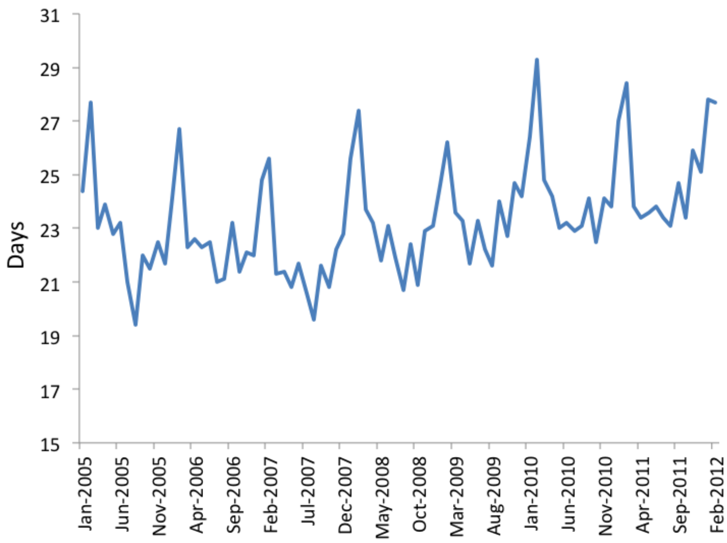
Second, in addition to production adjustments, the storage of gasoline would also help absorb small biofuels supply shocks. However this auxiliary channel has limited capacity and is designed to cover demand shocks and shocks coming from the supply side of fossil fuels. The existing gasoline storage network may not be enough for the added pressures of a scaled biofuels sector, especially one where the magnitude of supply disruptions is greater than that for fossil fuels. Figure 3 presents the average number of days of demand that the current storage of gasoline in the U.S. can support.

Third, from a firm-level perspective at small scales of production, some spare capacity will exist in the market which will be used to compensate for a negative shock. Once the scale of demand increases (both in an absolute measure and also as a proportion of the total crop harvested) the production of crops would be closer to its maximum capacity and thus less free capacity will be accessible. This phenomena may reverse once several firms start growing or purchasing feedstock in large-scale at separate locations. Assuming that shocks to different locations will not be perfectly correlated, firms can form a risk-sharing mechanism by exchanging their surplus or deficit of crop harvest.

2.2.2 First versus Second Generation Biofuels

Risk exposure and risk management strategies of biofuels firms change substantially when production shifts from first to second generation bio-

Figure 3: US Days of Gasoline Stock (Source: EIA)



fuels. There are key technical and economic differences between the structure of the production networks for the two generations of biofuels, which suggests several distinct risk-related concerns.

Technical Differences. From a technical point of view, first-generation biofuels use crops which have been engineered for several decades to be resilient and high-yield. Second-generation biofuels may be less efficient in this respect, depending on the feedstock crop. The harvest cycle also has significant implications for the speed of recovery from an adverse shock, whether for first or second generation fuels. Annual crops not only have a shorter cycle of recovery, but making changes to the land allocation pattern is also faster and easier for these crops as compared to perennial ones.[13] Here, algae-based second-generation biofuels can have an advantage over both annual and perennial crops, because of their harvest cycle of only a few weeks. This will substantially increase the speed of adjustment in production.

Markets. First-generation biofuels fit better to the structure of the spot market as there exist many local and global markets for corn, sugarcane, and other major agricultural products. In contrast, second-generation biofuels may either come from specialized feedstock (e.g. algae) or from agriculture residues (e.g. corn stover) or grasses for whom an active spot market may not exist (at least in the short-term). It is conceivable that biofuels firms would form a specialized spot market for these types of

[13]Production of perennial crops include large sunk costs. When the uncertainty about the future yield and price of a crop is high, the option to wait (to adjust production) will be valuable. The option value reduces the responsiveness of investment in production of this type of plant to instantaneous changes in the market demand. (see Price and Wetzstein (1999))

feedstock in the future. However, the size of the feedstock market (in expectation) will be matched to the magnitude of demand in the biofuels industry. Given the absence of other demand sectors for these feedstocks, there will be a limited ability to exchange excess demand with an alternative demand sector.[14]

Food-Fuel Competition. The effect of food demand volatility is also different for first versus second generation biofuels. For first-generation fuels, food and fuel compete for the same feedstock. Therefore, an increased demand for food will put pressure on the available feedstock for biofuels (in equilibrium it will increase the market price of feedstock, reducing the competitiveness of biofuels). That scenario would be reversed for second-generation biofuels because the food and fuel sectors will compete for separate parts of the plant (e.g. in the case of corn stover) if at all. An increased demand for food will increase the supply of feedstock for biofuels.[15]

The future growth path of second-generation biofuels is still uncertain and it is not clear which type of feedstock will play a dominant role. There are multiple feedstock options (algae, agriculture residues, grasses, woody feedstock, waste, etc.) and each of these feedstocks have a different risk profile with respect to the measures described here. Given that the development of second generation technologies is highly supported by public R&D funds, the resilience of feedstocks could provide an additional measure to be applied in choosing high-priority feedstock technologies to support.

2.2.3 Input Market Structure and Contractual Setups

The riskiness of the biofuels supply chain also depends on the economic and legal structure of the market. The market structure dimension can be divided into two major cases: when there is an active market for the feedstock (called the *spot market* case) and when there is no spot market. Within each market structure two major contractual setups of ex-ante versus ex-post order placement emerge. We discuss a combination of these four cases.

Existing Spot Market. Spot markets are formed when there are a large number of sellers and buyers whose output/input (respectively) are similar and can be supplied with similar costs. Within this market structure we distinguish two cases for the contractual setup in the feedstock market. The first one, which we call a *specialized supplier* case, is one in

[14]Woody feedstock would be an exception to this statement if there exist district heating facilities or power plants which are able to process or use that type of feedstock. In this case, the excess supply of feedstock can be sold to these plants.

[15]This statement is true only up to the point where the demand for biofuels feedstock does not exceed the available agriculture residue. Otherwise, producing feedstock for biofuels (e.g. switch grasses) may create a new round of food-fuel competition through land allocation.

	Ex-ante Order	Ex-post Order
Spot Market Exists	Lower price risk, higher quantity risk	Lower quantity risk, higher price risk
No Spot Market	Major quantity risk	Both quantity and price risks

Table 1: Market Structure and Contractual Setup

which a biofuels producer has long-term contracts with one or few suppliers that produce mostly for that biofuels company. Under this setup purchase orders are placed ex-ante (usually before the harvest season) and the specialized supplier commits to provide certain units of feedstock with a pre-specified price. The discrepancy between the delivered order by the supplier and the realized needs of the biofuels company can be procured from the spot market (also called an arm's length strategy). This method reduces the price risk for the biofuels company (compared to the case of procuring solely from the spot market) but exposes it to the random yield of the specialized supplier. Alternatively, a biofuels company can purchase the required quantity of feedstock from the existing spot market without having a procurement relationship with certain suppliers. Spot markets are usually large compared to the size of a single company, thus there is less quantity risk. However, the spot market price is volatile, exposing the firm to price risk.

Absent Spot Market. Procurement strategies of ordering ex-ante or ex-post can be followed when no active spot market exists. In practice, many biofuels producers currently operate under this setup because there is no existing spot market for the type of feedstock they are require (this is especially prevalent in the case of second-generation fuels) (Epplin, Clark, Roberts, and Hwang (2007)). Firms will tend to either produce the feedstock directly or form long-term relationships with local producers. Absent the spot market it is more difficult to purchase (or sell) additional quantities of feedstock to or from other suppliers or buyers if ex-ante placed orders fail to match the exact feedstock demand of the producer ex-post.

Table 1 provides a summary of these four cases, with a focus on price and quantity risk levels under each setup. The riskiness of each strategy is compared to the other strategy within the same market structure.

We conclude from Table 1 that a firm producing second-generation biofuels will face quantity risk until an active market for the feedstock is established. One mechanism which may lead to formation of such a market is to have multiple large biofuels companies that can trade the deficit or surplus of their dedicated production sites with each other.

3 Proposed Resilience/Risk Measures

A system subject to random shocks will exhibit stochastic behavior, however these risks can be managed and mitigated using risk management measures. Therefore, it is reasonable to distinguish the level of basic risks (uncovered or unmanaged risks) from the level of risks which are present even after implementing optimal risk management measures. We use the term "resilience" to refer to the ability of a system to deal with risks. More formally:

$$\text{Resilience} = f(\text{risks}, \text{risk management}) \tag{1}$$

The optimal level of risk management is an endogenous variable which is a function of the expected magnitude of risk as well as the structural parameters of the system. We propose the following general metrics for analyzing the resilience of a supply chain:

1. Vulnerability of demand side to supply shocks
2. Magnitude of shocks to major nodes of the supply chain
3. Frequency of adverse shocks
4. Duration of shocks (or the speed of recovery)
5. Availability of alternative sources

Mathematically, we can think of supply capacity as a mean-reverting process with a time-varying long-run mean which is subject to both diffusion (continuously-changing) and jump-type (a sudden change in the supply capacity, mostly due to disruptive events) shocks:

$$dS = \mu(\overline{S} - S)dt + \sigma dW + Kdq \tag{2}$$

This is a schematic representation where S is the current baseline level of supply, μ is the speed of mean-reversion (which captures how quickly the systems returns to its long-run mean after being hit by a shock), $\overline{S}$ is the long-run (equilibrium) level of supply. dW is the standard diffusion term (continuous shocks) and dq is a unit-size Poisson process (with an intensity parameter λ) capturing sudden shocks. σ and K capture the magnitude of shocks. The λ parameter of dq captures how often shocks affect the system.

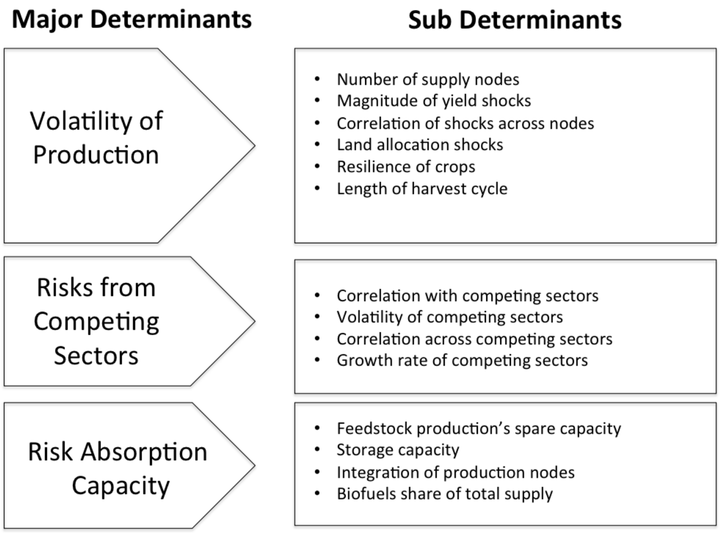
We assume that $\overline{S}$ is itself a dynamic process, changing over long time periods due to factors such as improved technology and increased land allocation.

$$\frac{d\overline{S}}{\overline{S}} = \mu_S dt + \sigma_S dW_S \tag{3}$$

where μ_S is the expected growth rate of baseline supply and σ_S is the volatility of growth rate of baseline supply.

We now turn to a discussion of the more fine-grained determinants of risks, and opportunities for risk management (which together determine the resilience, Equation 1) Total risk to the biofuels market (from a single firm as well as the industry-level perspective) can come from either the net supply of feedstock (the total production of feedstock excluding those allocated to other usage such as food) or from changes in the demand for biofuels. Figure 4 presents major factors determining the level of risk on the supply side. These include risk factors at the total supply level as well as the volatility of demand for competing uses of crops and feedstock. Figure 5 provides a list of factors determining risk exposure from the demand-side (changes to demand for biofuels or substitutes).

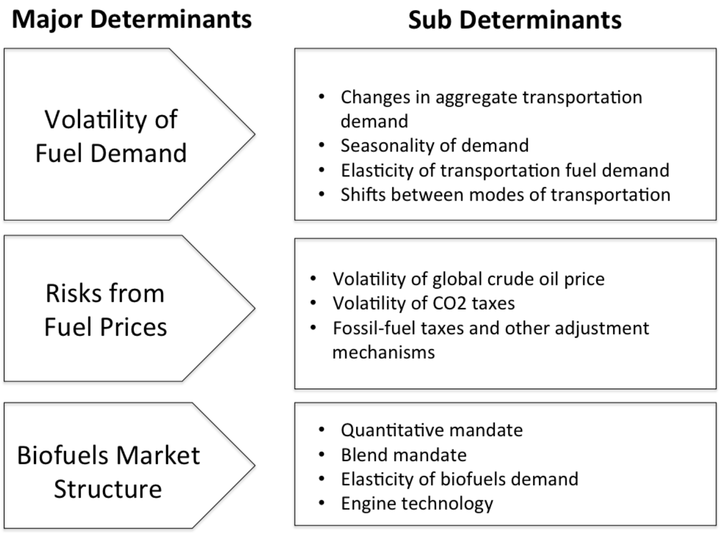
Figure 4: Determinants of Supply-Side Risks



4 Options for Risk-Management Strategies

Depending on technical and economic constraints, biofuels producers as well as the market can adopt various risk-management strategies. Strategies can range from storage (of the feedstock, pre-processed feedstock, or final biofuels), choosing a more resilient production technology (e.g. designing processing technologies for more resilient crops), feedstock diversification (e.g. developing technologies which can process multiple feedstocks), geographical diversification (e.g. purchasing feedstock from and locating plants in multiple regions or countries), using risk-management contracts and instruments and using flexibility in the supply of fossil fuels

Figure 5: Determinants of Demand-Side Risks



to cover the shortfall in the supply of biofuels. In this section we discuss in some detail strategies for risk mitigation via storage, diversification (both crop and geographical diversification) and risk-sharing using the fossil fuel sector. Table 2 provides a summary of risk-management strategies and the determinants of their effectiveness.

4.1 Storage

Storage technologies provide an inter-temporal buffer to smooth out random shocks to supply of and/or demand for commodities, and consequently reduce their price volatility (see Williams and Wright (2005)). Currently, there is some storage of ethanol in the US market. Figure 6 shows the time-series of ethanol stocks which suggests a sharp increase in the level of ethanol storage. Given that the supply of biofuels is approximately one million barrels per day, this graph implies an average stock of biofuels for 25 days. This level of storage is very close to the number of days gasoline stock can cover (reported in Figure 3) .

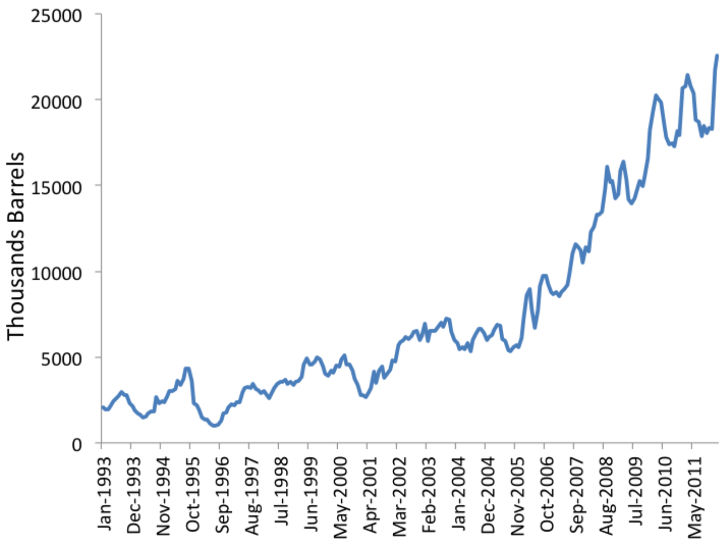
However, storage as a risk mitigation option faces limitations under the following contingency scenarios:

- If the decay rate of stored commodities (feedstock or final fuel) is high or if the stored material requires special conditions to store, the marginal cost of storage (per unit of time) would be high. This is the case for several feedstocks.
- If the cost of building a specialized storage facility is high it is not likely to be built.

Risk Management Strategy	Major Determinants of Effectiveness
Storage	Construction cost of storage facility Operational costs of storage Decay rate of stored products Opportunity cost of storage (interest rate) Temporal correlation of shocks Volatility of market
Feedstock diversification	Flexibility of a single processing unit to use multiple feedstock Cost competitiveness of multiple feedstock Correlation of shocks to various feedstock
Geographical diversification	Cost of transporting feedstock versus biofuels Cost competitiveness of multiple production centers Import and export policies and tariffs Correlation of shocks across regions Importance of economies of scale in production
Risk shifting to the fossil fuel sector	Flexibility of biofuels mandates Flexibility of car engines to change the blend ratio Existence of spare capacity in the fossil fuel refinery sector
Reducing feedstock supply volatility	Ability to produce in less risky regions Ability to improve the resilience of crops

Table 2: Summary of Risk Management Strategies

Figure 6: U.S. Ending Stocks of Fuel Ethanol (Source: EIA)



- Storage will not stabilize the system if (ex-post) realized shocks are highly correlated with each other over time or space, and the overall shortfall exceeds reasonable storage capacities. An example would be when bad harvest takes place over several subsequent years.
- If the realized supply shock is large for any other reason (extreme events) then storage will not be able be absorb the shock.

4.2 Diversification Strategies

Assuming a stable land-use pattern, where the share of land allocated to biofuel feedstock does not change substantially from one year to another,[16] the volatility of feedstock supply depends on factors such as temperature, precipitation, disease, and pest attacks. Basic intuitions from portfolio theory suggest both crop and geographical diversification may contribute to reducing the aggregate exposure of biofuels producers to adverse crop yield shocks. Both for a large biofuels company and from societal perspective crop diversification is an option. As a concrete example, the European biofuels industry uses multiple feedstocks such as rapeseed, soybean, palm oil, sunflower and animal fat. A limiting factor for diversifying crops is that various crops should have comparable production costs. Otherwise, the efficiency loss from using multiple crops may exceed the benefits of risk reduction through diversification.

The same cost-benefit analysis (cost efficiency versus risk reduction) applies for the geographical diversification strategies. For the geographical

[16]This assumption can questioned when the scale of production changes.

diversification strategy to be effective and optimal, some conditions must hold. We enumerate them briefly.

- Different locations must have sufficiently low spatial correlations for precipitation, temperature, weather events, diseases, and pest infestations. Otherwise, diversification will not reduce the total volatility in a significant way.[17]
- The benefits from lower yield correlations between different regions should outweigh the additional costs of losing economies of scale (e.g. Wetterlund et al. (2012)). The need to establishing multiple smaller-scale plants instead of a large central plant may raise capital, transaction and coordination costs, creating diseconomies of scale.
- Diversification is more beneficial if biofuels producers are limited to using long-term supply contracts for specialized feedstock which specify orders of feedstock in advance. In this case the purchase of feedstock cannot be adjusted ex-post to be matched with the available production quantity and hence having a diversified portfolio is valuable.[18]
- The cost of transporting the output (i.e. biofuels) from distant locations should be small and the cost of transporting feedstock should be high. If the cost of transporting input is small, producers do not need to locate their plants in different locations but rather can purchase feedstock from a diverse geographic base (assuming there is a market for this). If the transportation of output is too costly, a diversification strategy will not be followed because the additional cost of transporting fuel from various regions may be higher than the benefits of risk-management.

4.3 The Fossil Fuels Sector as a Shock Absorber

At present, biofuels and gasoline are not perfect substitutes due to engine technology limitations. Moreover, mandates dictate a fixed quantity (in the case of the U.S.) or a percentage of blend (for E.U. countries) for biofuels. Both mandates prevent fossil fuels and biofuels from serving as perfect substitutes. However, if these limitations are removed in the future, as is anticipated by some, vehicles will be able to easily switch between the two. From the perspective of consumers this creates a valuable option for managing market risks by increasing the supply of one of two

[17] We use FAO data and calculate the correlation matrix of yield residuals of maize for a group of large countries. Our results suggest that yields in different locations have low correlations (and even negative in some cases). This result supports the argument that geographic diversification can reduce the variance of the total fuel portfolio.

[18] The ability to procure feedstock from local producers ex-post (with additional costs) creates an option value. The optimal diversification strategy should consider the tradeoff between using this option versus relying on multiple producers from different locations.

fuels when the supply of the other one faces a negative shock. The option is particularly valuable given the fact that the supply of biofuels and fossil fuels have low correlation (except for extreme cases of a weather event which destroys infrastructure for both). However, this risk-management channel is less productive under the following conditions:

- When the demand for food and fuel are highly correlated. In this case positive economic growth shocks can put pressure on both biofuels and fossil fuels, especially in the case of the first-generation biofuels.
- When the fossil fuels infrastructure (i.e. refiners, pipelines, storage facilities and stations) does not have enough spare capacity and the ability to adjust quickly. Since no sector is interested in operating at a low utilization rate (i.e. having a large spare capacity) over the long-run, it is expected that the risk-shifting through swapping between fuels would be limited in a large-scale scenario.

Additionally, an integrated market of fossil fuels and biofuels could increase the risks for biofuels producers because their effective demand will be subject to shocks to crude oil prices. If crude oil prices drop significantly, consumers will switch to fossil fuels and the demand for biofuels will drop. On the other hand, if crude oil becomes expensive biofuels firms will have a large margin and will make a large profit. This scenario increases the volatility of the net profit of biofuels producers.

5 Conclusion

We provided arguments to support the claim that the supply of biofuels can be risky and that these risks become more important as biofuels' contribution to transportation fuels increases. We also provided a list of metrics to use in evaluating the riskiness of a biofuel supply chain. Finally, we review a set of possible risk reduction strategies, and discuss in some detail two major risk management strategies, storage and diversification.

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