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Logistical supply chain design for bioeconomy applications

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ABSTRACT

This paper proposes and tests novel supply chain designs for bioenergy and biobased products that result in logistical costs savings of 2–38%. The proposed supply chain design reduces the costs of: (1) purchasing logistical harvesting equipment; (2) operating logistical harvesting equipment; and (3) holding feedstock inventory, by using a multitude of crop types as feedstock, instead of just one, as is common in research and practice today. In so doing, this research challenges the prevalent assumption that monocultures, despite their known environmental concerns, are preferable from a costs perspective. Simulation/optimization is used to test supply chain designs, and then to find the environmental conditions where these new supply chain designs could be most profitably implemented.

1. Introduction

Biorenewable fuels have the potential to offset worldwide carbon and greenhouse gas emissions, develop local economies in rural areas, and enhance energy security in the countries in which they are produced [1]. That has spurred significant public and private interest around the world. By federal mandate in the United States, biorenewable fuels production will grow to 36 billion gallons in 2022. Similarly, the European Union has stipulated that the European biorenewable fuels industry grow to meet 10% of its transportation fuel demand by 2020 [2].

The vital role that reducing logistical costs will play in determining the feasibility of a future bioeconomy has been widely published. Hess et al. have suggested that inbound feedstock costs will "largely control the rate at which the industry grows" [3]. Various authors have attributed from 35% to 90% of supply costs for biobased products to logistics under various circumstances [4,5]. Logistics has thus been pinpointed as a significant cost component and potential obstacle to future development of the bioeconomy [4,6–8].

Research logisticians have recently been called to: (1) seriously address fuel use and natural resource use [9]; and (2) design smart logistical plans for the profitable development of more sustainable industries [10]. However, mainstream logistics research has only scantly considered supply chain design in the context of many developing sustainable industries, especially biorefining and biobased products (e.g. Ref. [11]).

In the United States and around the world, supply chains for biorenewable fuels and biobased products are currently

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being researched and implemented in the seemingly tried-and-true mold of conventional food agriculture—that is, by imagining gigantic swaths of land planted year-after-year to a single, high-yielding feedstock crop that surrounds the biorefinery. In both food and biofuel production systems, this, unwitting, supply chain design is referred to broadly as "monoculture", and is exemplified by modern corn-to-ethanol production in the United States (the world's largest ethanol producer); sugarcane-to-ethanol systems in Brazil (the world's second largest ethanol producer); and also by researchers' and politicians' visions of advanced switchgrass-to-ethanol facilities that, they argue, will become technically and economically feasible in the next 10–15 years.

That the agricultural and biorenewable world has come to embrace monocultural supply chain designs is—like all past—already prologue, and has been well documented from a variety of perspectives [12–14]. Similarly well-documented—although, rarely implemented in modern practice—are the ecological and agronomic reasons to believe that the alternative, more diverse supply chains, that employ a variety of crops on the landscape, could benefit both productivity and environmental stewardship [15–17]. Do business logisticians now have a role to play in this ongoing discussion about changing the future of global agricultural landscapes? This research suggests that we do. The authors suggest that designing supply chains for biobased products that employ multiple crops as feedstock offers distinct logistical cost advantages compared to contemporary practice and research.

In so doing, this research challenges the prevalent assumption that monocultures, despite the problems already researched, are preferable mostly from a costs perspective. The authors suggest that logisticians have a prominent role to play in this discussion. Specifically, the question that this research addresses is: from a logistics and inventory cost perspective, is the traditional monocultural supply chain design the least cost approach given varying environmental circumstances? This paper contributes to the literature by exploring how, and under which conditions, heretofore overlooked savings can arise from using multiple crop types as feedstock instead of only one.

1.1. Previous research

The techno-economic research literature to-date is not without suggestions for supply chain design in the biorenewable context. Recent reviews can be found in Refs. [18–20]. In their review, An et al. note the relative absence of strategic thinking about supply chains for biofuels compared to the research attention paid to day-to-day operational issues. While a wealth of papers have been written on techno-economic assessment of facility placement and technology choices, fewer have considered questions of supply chain design. Notable exceptions include Tatsiopoulos and Tolis [21], who compared both centralized and decentralized logistical systems, as well as farmer versus third party carriers for corn stalks in Greece. They found that decentralized systems, where farmers themselves were responsible for trucking, resulted in the lowest possible logistical costs in their case study area. Sokhansanj et al. [22,23] have evaluated four ways in which switchgrass could be prepared and stored for truck transportation (square bales, round bales, loafing and wet baling). They found that storing the material in roadside loafs, and then grinding it before loading it on to grain trucks was the most cost effective at smaller sizes, but that square baling at the roadside, and then transporting square bales to the refinery on flatbed trucks became more cost competitive as plant size increased. Kanzian et al. [24] used linear programming and GIS to consider setting up intermediate chipping facilities between the forest supplying a biorefinery with woody biomass and an Austrian biorefinery. They found that the intermediate chipping facilities were not cost effective. Fan et al. [25] outlined four archetypal supply chains for cellulosic biofuels and found the most cost effective and environmentally responsible design depended on the size of the facility under consideration.

What has been overlooked in recent imaginations and reviews of supply chain design for biofuels are the potential costs savings of using multiple crops instead of a single one. In Gold's excellent recent review piece, the logistical problems endemic to monocultures are presented; but the review leaves the emerging evidence that using multiple feedstock crops could provide a solution untouched. Nilsson and Hansson [7] used a discrete event simulation approach to find that a two-crop system offered cost savings in terms of inventory and logistics at one district heating plant in Sweden. Papadopoulos and Katsigiannis used dynamic programming to optimize a biorefinery in Greece, and noted that their optimal solution sets contained multiple types of feedstock coming in to the refinery, not just one [26]. Similarly, in a case study application of their proposed metaheuristic facility citing and plant optimization model in Greece, Rentizelas et al. reported optimal solution sets that used four crops as feedstock instead of only one [8].

What we do not yet know is how robust and generalizable are these emerging findings. Research logisticians have yet to elucidate the mechanisms under which these savings arise, and to investigate under which technological and environmental conditions one could expect to see meaningful logistical savings from multiple feedstock supply chain designs? This is the research gap addressed by this paper.

1.2. Research implications

Because of the projected growth of biorenewable fuels around the world, this potential re-design of supply chains (and thereby very large-scale land use) carries dramatic implications for practitioners and the communities around the world that will be engaged in the bioeconomy. This paper suggests that biorenewable investors and plant operators stand to save up to 38% on the cost of delivered feedstock by re-imagining their supply chains to include multiple crops instead of just one. Companies that seize this opportunity would dramatically re-design agricultural land use around the world and could make the global transition away from fossil fuels more feasible in our lifetimes.

We call the logistical benefits proposed to arise from using multiple feedstock crops 'the benefits of diversified supply chains', and present conceptual arguments for their cost savings mechanism in Section 2. In Section 3, a simulation/optimization experiment with 81 treatment scenarios is

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