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Research Article

Potential for Pennycress to Support a Renewable Jet Fuel Industry

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Abstract

Pennycress, an oilseed plant with high oil content, is being considered as a second-generation biofuel feedstock. The plants lifecycle fits with traditional U.S. crop rotations. This study examines the economic feasibility of pennycress production, its potential to supply a renewable aviation industry and its potential impacts on the U.S. economy. Incorporating pennycress in U.S. crop rotations at a price of $0.20 per pound stimulates 22.1 million acres of pennycress to be planted and increases harvested acreage of corn and soybeans by 3.2 percent and 5.0 percent, respectively. To produce 800+ million gallons of jet fuel, 22 HEFA facilities fed by 43 oil extraction facilities are required resulting in the addition of $19 billion to the nation's economy and nearly 66,000 jobs.

Keywords: *Pennycress; Alternative Aviation Fuel; Biojet Fuel; IMPLAN; POLYSYS*

Introduction

The commercial aviation industry consumed over 16.2 billion gallons of jet fuel in 2014, accounting for approximately 25 percent of operating expenses [1]. With such a large proportion of operating expenses coming directly from fuel consumption, fuel price uncertainty can have a substantial impact on airline operating strategies. Airlines use various strategies to manage fuel price uncertainty, including adjustments in aircraft size and utilization, flight-route and destination offerings, vertical integration and financial hedges [2]. The use of renewable jet fuel has the potential to decrease fuel-price uncertainties, thereby decreasing fuel-hedging costs, and decreasing profit volatility. The United States Government is actively supporting the development of renewable jet fuels. Two examples of this are the Farm-to-Fly 2.0 program, which focuses on supply chain and infrastructure, and the Commercial Aviation Alternative Fuels Initiative (CAAFI), which facilitates research and development, environmental assessment, fuel testing, demonstration and commercialization. As of 2015, the standard setting organization, ASTM International, has approved five renewable jet fuels for use in aviation [3]. This analysis examines the potential for pennycress (*Thlaspi arvense*) as a jet fuel feedstock to support a renewable jet fuel industry in the United States.

Pennycress (*Thlaspi arvense*), commonly referred to as "stinkweed" or "French-weed" and found throughout the United States [4], has the potential to supply both oil and biomass to the biofuels market. Following harvest, seed crushing and pre-processing, pennycress offers a suitable oil to allow conversion to a Hydroprocessed Esters and Fatty Acids (HEFA) fuel. Pennycress provides the benefits of a winter cover crop while also supplying farm producers with direct economic benefits. As a winter cover in double crop rotations, pennycress is established in the fall and harvested in mid-to-late-spring. Pennycress can offer the benefits of weed reduction, excess nutrient uptake and management, disruption of pests and pathogens, and hydrological regulation by aiding in the drying of excessive soil moisture. Pennycress can grow on fallow winter land, providing a valuable cash crop, which avoids the pitfalls of the food-versus-fuel debate [5].

HEFA fuels are a second-generation alternative fuel that can be blended at 50/50 ratio with conventional jet fuels. This fuel can reduce greenhouse gas emissions by 65-85 percent compared with conventional jet fuels and has shown higher energy density in flight, allowing aircraft to fly further on less fuel. It is also a drop-in replacement fuel, which requires no changes to aircraft technology or fuel infrastructure [6].

The objective of this study is to examine the economic feasibility of a pennycress to renewable aviation fuel, plus evaluate the potential economic impacts this industry could have on the U.S. economy. The objective is achieved by developing pennycress enterprise budgets and yields associated with pennycress production (Table A.1) and allowing pennycress rotations to compete for land use with other crops at a range of pennycress prices using POLYSYS, a partial equilibrium simulation model of the US Agricultural Sector. A pennycress scenario was modeled by the addition of a corn/pennycress/soybean rotation with offered prices to pennycress and compared to a baseline without a pennycress price offered. County total land use change was limited to 25 percent. The analysis was simulated from 2015 to 2039 at $0.05 price increments ranging from 0.05 and 0.50/pound. Most of the results presented in this manuscript represent the production levels that occur at $0.20 per pound. The POLYSYS results, under the $0.20 per pound scenario, were placed into a national IO model, IMPLAN [7].

Materials and Methods

Figure 1 provides a schematic of information flow for the

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Appendix **Table A.1:** Pennycress Cost of Production Budget.

		Units	Quantity Units	Price $/Unit	Total $/Acre
Revenue:	Pennycress [1]	lbs	1193	$0.20	$238.60
Total Revenue					$225.00
Variable Expenses:					
	Seed [2]	lbs	5	$2.50	$12.50
	Fertilizer & Lime	Acre	1	$28.50	$28.50
	Chemical [3]	Acre	1	$0.00	$0.00
	Repair & Maintenance [4]	Acre	1	$10.46	$10.46
	Fuel, Oil & Filter [4, 9]	Acre	1	$5.90	$5.90
	Operator Labor [4, 9]	Acre	1	$5.33	$5.33
	Machinery Rental [5]	Acre	1	$10.00	$10.00
	Crop Insurance [6]	Acre	1	$0.00	$0.00
	Operating Interest [7, 9]	percent	$72.69	6.00%	$2.18
	Other Variable Costs	Acre	1	$0.00	$0.00
Total Variable Expenses					$74.87
Return Above Variable Expenses					$163.73
Fixed Expenses:					
	Machinery [4, 9]				
	Capital Recovery	Acre	1	$23.25	$23.25
	Other Fixed Machinery Costs	Acre	1	$0.00	$0.00
	Property Taxes	Acre	1	$0.00	$0.00
	Insurance (Non-Machinery)	Acre	1	$0.00	$0.00
	Other Fixed Costs [8]	Acre	1	$0.00	$0.00
Total Fixed Expenses					$23.25
Return Above All Specified Expenses					$140.49

1) There is not yet an established market for Pennycress seed. The Agricultural Marketing Resource Center (AMRC) provides an estimate of $0.15 per pound of seed. Field trials have resulted in yields ranging from 1400 to 2200lbs per acre.

2) Seed costs are projected as provided by the AMRC

3) No additional fieldwork is required from the time of planting to harvest because no insecticide or herbicide applications are required for a successful Pennycress crop. As a member of the mustard family and a winter annual, insect pressure is insignificant due to its natural chemistry and the temperatures of the growing season thus limiting an insecticide requirement. (http://www.growpennycress.com/farming.html)

4) Machinery expenses will vary dramatically by operation, financial resources, and land base. The machinery cost estimates provided in Table 3 are provided as an estimate of cost of ownership and operation for specified pieces of machinery that would be available to a "representative" row crop farm in Tennessee.

5) Aerial Seeding over standing corn. Cost per acre represents the per acre hire rate for an aerial seeding operation. Source: [23]

6) Crop insurance is not currently available for Pennycress based on discussions at the Inaugural Pennycress Workshop

7) Operating interest is based on half of all variable expenses.

8) Additional costs may be incurred due to specialized equipment required in the handling, hauling, and storage of pennycress.

9) Semi-Tractor/Trailer Machine Hours are based on an 800-bushel capacity or 40,000 lbs per load. Given a yield of 1600 lbs per acre, one load is equal to 25 acres of yield

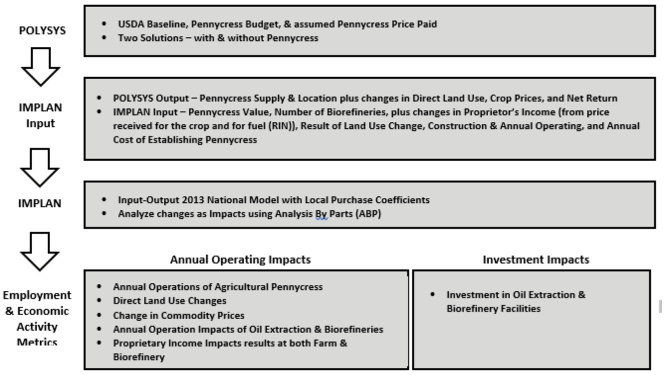

Figure 1

study. Two models are used – POLYSYS and IMPLAN. The output from POLYSYS is used to develop economic impact input data for IMPLAN.

Two Models Employed

POLicY Analysis SYStem (POLYSYS)

Estimated county level yields and variable costs are used to generate national and regional supply curves using a partial equilibrium model known as the POLicY Analysis SYStem (POLYSYS). The POLYSYS model simulates changes in land management, crop production, farm income, government payments, and commodity prices from a baseline solution. The model has theoretical underpinnings to an equilibrium displacement model, or EDM [8]. EDM's are used to evaluate exogenous shocks to the equilibrium market, which result in changes to variables that are endogenously determined by the system. The equilibrium market is represented by a published baseline of current and projected agricultural sector characteristics. The published baselines are provided by the United States Department of Agriculture [9].

Each simulation of POLYSYS imposes one or more changes to the baseline scenario, acting as an exogenous shock on the equilibrium, which results in adjustments to the endogenous variables, agricultural supply, demand, prices, and income. Thus, each simulation can be thought of as a series of multi-period, annual adjustments to the EDM with the system of equations organized into four interdependent modules. The four core modules include national livestock supply and demand, regional crop supply, national crop demand and a national agricultural income module. Key inputs into the model include a baseline agricultural outlook, national land use, agricultural management practices (i.e. crop inputs and yields), livestock sector data (i.e. forage requirements), agricultural sector policy data such as government payments, and economic indicators such as demand elasticities and land use shift coefficients. For each U.S. county, the crop supply module first estimates the available acreage for the nation's major crops for barley, corn, cotton, oats, rice, sorghum, soybeans, and wheat along with hay. The exogenous shock, in this case a price being offered to pennycress, alters the relative profitability of competing crops, and the allocation mix changes as a result based on maximization of expected returns. After supply is determined, a national price for each program crop is estimated based on price elasticities in the demand sectors.

Pennycress production is potentially an additional net return to the corn/soybean producer. In this study, POLYSYS is used to estimate crop supply, including the supply of pennycress, at the county level for the 48 continental United States. Pennycress is introduced to the POLYSYS framework as a triple-crop enterprise of corn-pennycress-soybeans, which competes for land among the other crop enterprises. County land use changes are limited so that the maximum allocation of cropland permitted to pennycress is 25 percent. Furthermore, soybean yields are modeled to have a 6.5 percent reduction in yield assuming a 24-day planting delay when preceded by pennycress [10]. Regional supply results are then aggregated to the national level to examine the supply potential of pennycress and resulting impacts on price and acreage of corn, soybeans, grain sorghum, oats, barley, wheat, cotton and rice. These price impacts are then fed into next year's decision framework. Performance indicators developed from POLYSYS output and used in this analysis include establishment and production of the feedstock, along with changes in direct land use, commodity prices, and farmer profits.

IMpact Analysis for PLANning Model (IMPLAN)

A national IMpact analysis for PLANning model (Minnesota IMPLAN Group) – an input-output (IO) regional economic impact model – is used to estimate the economic impacts of the aviation biofuel supply chain on regional economies (i.e., constructing and operating the biorefineries and preprocessing facilities, establishment and production of the feedstock, land use changes, commodity price changes, proprietor profits/losses, and farmer profits). Excluded from this analysis are the costs of transporting the pennycress seed to the oil extraction facility, the costs of transporting the oil to the conversion facility, and the costs of moving the final product since it is not known where these facilities will be located. The IO modeling framework analyzes the interdependence of industries in an economy through market-based transactions. Output from the model includes descriptive measures of the economy such as total industry output (a measure of economic activity), employment, and labor income for 536 industries, along with corresponding changes in state/local taxes to regional (multi-county) or state level of analysis because of these changes.

The IO analysis provides estimates of output, employment and income multipliers, which measure the response of the economy to a change in demand or production. The multipliers measure the indirect and induced effects of a change in final demand (direct effects) for a particular industry (for example, the introduction of biorefineries and preprocessing facilities in a region). The indirect effects are the secondary effects or production changes when input demands change due to the impact of the directly affected industry (for example, construction sector, agriculture producers). The induced effects represent the response by all local industries caused by changes in expenditures by households and inter-institutional transfers (for example, households and state/local governments, etc.) generated from the direct and indirect effects of the change in final demand. Projections of changes in jobs (job creation), economic activity, labor income and state/local taxes to the state region both directly from growth in the aviation biofuel industry itself and through multiplier effects are projected using Analysis by Parts (ABP) methodology with a U.S. IMPLAN model.

The first step of ABP is splitting the impacts into respective parts. Instead of building a specific industry, the goods and services demanded from multiple industries to produce the impact are used. Production of renewable fuel can occur through a number of technological processes. One such technological process, which shows considerable promise, is HEFA capable of producing four different types of alternative fuel through the conversion of a vegetable oil feedstock. This technology can produce bio-jet, bio-diesel, LPG, and Naphtha [11,12]. While the Techno-Economic-Analysis (TEA) assumes that oil can be purchased, which may be adequate for a single plant, with an analysis of an industry, additional oil extraction facilities will be required. These facilities may be located at the conversion facility or elsewhere. The oil extraction industry's investment and operating budget was adopted from Georgia's Center for Agribusiness and Economic Development [13]. The budgets for both oil extraction and hydro processing facilities are assigned to IMPLAN sectors (Tables A.2 and A.3). The total impact is the sum of the impacts of all of the parts.

Two primary cost parameters utilized in this study are operating costs and capital costs (initial investment cost). English et al. (2016), provide a thorough review of operating and capital costs for a variety of production pathways [14]. Since pennycress is the chosen feedstock under consideration for this study, cost parameters represent the hydro processing of purchased pennycress oil. Crushing and extraction of pennycress oil is carried out by a dedicated facility. Seed-to-oil processing facilities add considerable value to the farm-gate value of pennycress. In addition, both the jet and renewable diesel fuels would qualify as an advanced biofuel and qualify for RINs.

Pennycress Budget and Yields

There is not yet an established market for pennycress and commercial scale production has not been widely established. However, the Agricultural Marketing Resource Center provides an estimate of $0.15 per pound of seed [15]. Enterprise budgets are developed to estimate the per acre cost of production for pennycress based on a maximum yield of 1,600 pounds per acre [15-17]. Total variable expenses are estimated to be $74.87 per acre assuming aerial seeding of five pounds per acre (Appendix Table A.1). Total fixed costs are estimated to be $23.25 per acre. Depending on the yield, breakeven prices are estimated to range from $0.06 to $0.12 per bushel, which were estimated from a yield range of 800 to 1,600 pounds per acre, respectively (Table 1). This is $0.03 to $0.09 below the estimated market price provided by AGMRC. Break even yield for a market price of $0.20 per pound is estimated to be 491 pounds per acre. This break-even price does not account for the opportunity, uncertainty, nor sunk costs in the decision to invest in pennycress production. Non-machinery insurance and property taxes are not included as it is assumed that these costs are covered by the primary crops corn and soybeans.

Pennycress is cold tolerant and can be grown over a wide set of conditions. However, the plant is sensitive to high heat conditions. Sharma et al. (2007) found that pennycress exhibits a higher freezing tolerance than *Brassica napus* (Canola) [18]. With a three-week cold acclimation period, pennycress is freeze tolerant at -16.8 degrees Celsius or less than 2 degrees Fahrenheit. Temperatures that exceed 85 degrees Fahrenheit pose a risk to pennycress and have an impact on pod and seed numbers [19]. Higher temperatures of 92 °F and above cause the plant to abort flowering [17]. To obtain regional yields for the United States, a lower bound of 5oF and upper bound of 88oF are used. September through May 2000 to 2014 monthly average high and low temperatures were collected by climate divisions within the continental United States. The frequency of reaching the lower and upper bound temperature is calculated within each year and climate division and then aggregated over the years 2000 through 2014. Median values range from zero to three over the sample. Therefore, it is assumed that a median of one will imply a 25 percent yield reduction, a median of two will imply a 50 percent yield reduction and a median of three will imply a 75 percent yield reduction. Using these assumptions, the potential yield for each county is calculated in the 48 contiguous states.

Fuel Production Estimates

Based on simulation results, the supply of renewable jet fuel can be determined by assuming a usage rate of supplied pennycress oil. In this case, the transportation sector is assumed to consume 100 percent of the supplied pennycress oil using a hydro-processed renewable distillate facility as the stylized conversion industry [11]. Oil extraction facilities are needed to extract the oil. Oil in wild pennycress can range from 36 to 40 percent [17]. This analysis assumes 38 percent oil

Appendix **Table A.2:** Oil Extraction Facility Investments and Annual Operating Expenses.

IMPLAN Sector	IMPLAN Sector Description	Transactions	
		Single Facility	Industry
Investment:			
53	Newly Constructed Manufacturing Structures (Buildings/Structural, Installation, Electrical, Foundation, Fire Protection, Excavation, Roads/Parking, Utilities, Offices/Storage)	$9,950,000	$427,850,000
243	Boiler (Plant Infrastructure)	$800,000	$34,400,000
244	Metal Tanks (Heavy Gauge) (Preparation Equipment, Extraction Equipment, Oil/Hexane Storage)	$6,900,000	$296,700,000
277	Air Conditioning, Refrigeration, & Warm Air Heating Equipment (Cooling Tower (Plant Infrastructure))	$250,000	$10,750,000
291	Preparation Conveying (Crush plant)	$350,000	$15,050,000
449	Engineering/Construction Management	$3,500,000	$150,500,000
Annual Operating:			
49	Electricity Transmission & Distribution (Total Energy)	$1,503,800	$64,663,400
51	Water, Sewage, & Other Systems (Total Sewer/Water)	$29,700	$1,277,100
165	Other Basic Organic Materials (Process Materials)	$85,000	$3,655,000
428	Wireless Telecommunications (Communications)	$1,100	$47,300
434	Nondepository Credit Intermediation & Related Activities (Interest on Operating Capital)	$167,000	$7,181,000
437	Insurance (Taxes & Insurance)	$185,000	$7,955,000
447	Legal Services (Protection & Safety)	$7,900	$339,700
448	Accounting, Tax Preparation, Bookkeeping, & Payroll Services (Professional)	$4,500	$193,500
454	Management Consulting Services (Manpower, Employee Related, Other)	$37,000	$1,591,000
457	Advertising, Public Relations, & Related Services (Admin & Marketing)	$1,500,000	$64,500,000
454	Management Consulting Services (Manpower)	$727,700	$31,291,100
454	Management Consulting Services (Employee Related)	$9,000	$387,000
471	Waste Management & Remediation Services (Water Treatment)	$30,000	$1,290,000
507	Commercial & industrial Machinery & Equipment Repair & Maintenance (Maintenance)	$300,000	$12,900,000
53	Newly Constructed Manufacturing Structures (Buildings/Structural, Installation, Electrical, Foundation, Fire Protection, Excavation, Roads/Parking, Utilities, Offices/Storage)	$813,239	$34,969,277
243	Boiler (Plant Infrastructure)	$130,772	$5,623,196
244	Metal Tanks (Heavy Gauge) (Preparation Equipment, Extraction Equipment, Oil/Hexane Storage)	$1,127,910	$48,500,130
271	All Other Industrial Equipment (Packaging)	$40,866	$1,757,238
291	Preparation Conveying (Crush plant)	$57,213	$2,460,159
			$290,581,100

Source: [13]

Appendix **Table A.3**: Transactions by Plant Capacity and IMPLAN Sectors.

		Transactions by Plant Capacity for		
IMPLAN Sector	IMPLAN Sector Description	2,000 bpd[a]	4,000 bpd	6,500 bpd
271	Hydrotreater	$919,800	$1,226,400	$996,450
271	Isomerizer	$1,533,000	$1,839,600	$2,989,350
291	Saturated gas plant	$306,600	$613,200	$996,450
244	Storage (liquid product, 25 days)	$306,600	$613,200	$996,450
53	Offsites, greenfield (50% of subtotal B)	$1,533,000	$2,452,800	$2,989,350
53	Special costs (4% of subtotal C)	$306,600	$0	$0
434	Contingency (15% of subtotal C)	$613,200	$613,200	$0
434	Escalation (2010 CEPCI)	$919,800	$1,226,400	$1,992,900
271	Maximum jet production	$306,600	$613,200	$0
164	Catalyst	$613,200	$1,226,400	$996,450
437	Insurance (0.5% of TPI)	$306,600	$613,200	$996,450
523	Local taxes (1% of TPI)	$613,200	$1,226,400	$996,450
507	Maintenance (5.5% of TPI)	$3,679,200	$5,518,800	$6,975,150
434	Contingency (10% of subtotal)	$613,200	$613,200	$996,450
271	Maximum jet production	$306,600	$613,200	$0
49	Electric power	$613,200	$1,226,400	$1,992,900
50	Natural gas	$4,905,600	$9,811,200	$15,943,200
162	Hydrogen purchase	$6,438,600	$12,877,200	$20,925,450
71	Vegetable oil	$83,395,200	$166,790,400	$271,034,400
271	Hydrotreater	$91,980	$122,640	$99,645
271	Isomerizer	$153,300	$183,960	$298,935
291	Saturated gas plant	$30,660	$61,320	$99,645
244	Storage (liquid product, 25 days)	$30,660	$61,320	$99,645
53	Offsites, greenfield (50% of subtotal B)	$153,300	$245,280	$298,935
53	Special costs (4% of subtotal C)	$30,660	$0	$0
271	Maximum jet production	$30,660	$61,320	$0
PI	Brownfield offsites credit (25% of subtotal B)	$919,800	$1,226,400	$1,992,900

[a]Barrels per day
Source: [11]

Table 1: Breakeven Costs for Selected Yields.

Yield (lbs)	Variable Cost ($/lbs)	Total Specified Cost ($/lbs)
800	$0.09	$0.12
900	$0.08	$0.11
1,000	$0.07	$0.10
1,100	$0.07	$0.09
1,200	$0.06	$0.08
1,300	$0.06	$0.08
1,400	$0.05	$0.07
1,500	$0.05	$0.07
1,600	$0.05	$0.06

content. From 100 pounds of pennycress oil, 7.22 gallons of jet fuel is produced along with 1 gallon of Naphtha, 3.28 gallons of renewable diesel, and 2.5 gallons of LPG (Table 2). The jet fuel and renewable diesel produced from this oil would qualify as an advanced biofuel and therefore receive RINS. In this analysis, the RIN value used is $1.00 per advanced biofuel gallon.

The simulation is carried out for years 2016-2039. A range of possible pennycress prices are utilized to draw out pennycress supply curves for this period. In the analysis below, the indicators represent an average over the time-period and capture the changes to the agricultural sector over the period 2016-2039.

POLYSYS Results

Pennycress Supply Over Time

The supply curve generated by POLYSYS shows that if pennycress seed receives a price of $0.20 per pound, enough feedstock could be produced to support an 800-million-gallon per year industry (Figure 2). When the market price for pennycress is $0.00, there is no pennycress production and the other solutions that have a positive pennycress price are compared to it (Without Pennycress or WOP). At a market price of $0.05 per pound of pennycress seed, pennycress comes into production. With a market price of $0.20, POLYSYS simulation results in an estimate of 22.1 million acres planted annually, with a national per acre average yield of 1,193 pounds. This translates to 9,685 million pounds of vegetable oil. Converting the vegetable oil to jet fuel using a hydro-processed renewable distillate facility will yield 813 million gallons of jet fuel, as well as significant levels of diesel (23.5 percent), Naphtha (7.1 percent), and LPG (17.8 percent), assuming nearly 14 gallons of fuel is produced from 100 pounds of oil (Table 3) [11,12].

Table 2: Estimated Fuel Production from a Hydro Processed Renewable Distillate Facility per 100 Pounds of Vegetable Oil.

Fuel Type	Fuel pounds	Conversion pounds/gallon	Fuel gallons
Jet Fuel	49.4	6.66-6.84	7.22
Naphtha	7.0	7.08	0.99
Diesel	23.3	6.93-7.37	3.28
LPG and Propane	10.2	6.66	2.48
Total Fuel	89.9	6.44	13.97

Sources: [12,20-22]

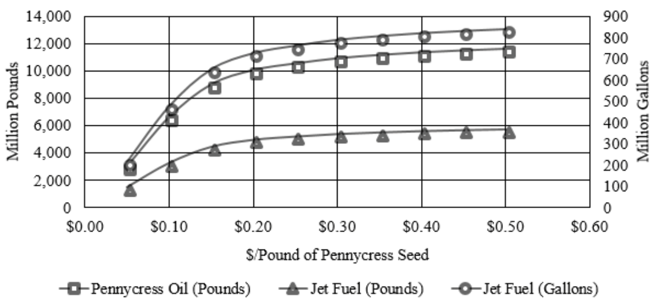

Figure 2: Average Estimated Pennycress and Biojet Fuel Production, 2016-2039.

Table 3 provides information on the potential supply curve for pennycress seed and resulting supply of renewable aviation fuel in millions of gallons. Pennycress has the potential to contribute a large supply of renewable aviation fuel to the market, particularly above the $0.08/pound threshold. The representative supply curve (red curve) is shown in Figure 2.

Direct Land Use Change

As pennycress production becomes more profitable, acreage shifts away from other crops while corn and soybean acreage increases. Table 4 presents the simulated results for eight primary crops -- corn, grain sorghum, oats, barley, wheat, soybeans, cotton and rice at a market price of $0.20 per pound of pennycress seed and a maximum yield potential of 1,600 pounds per acre. The baseline figures represent the case where there is no market for pennycress. With an existing market price of $0.20, an annual average of 22.1 million acres of pennycress are harvested. With the addition of pennycress rotation acreage, comes a slight increase in harvested corn and soybean acreage. In this scenario, harvested acreage of corn and soybeans includes single-crop and double-cropping methods. Therefore, total harvested acreage increases by 3.2 percent and 5.0 percent over the baseline scenario for corn and soybean, respectively, which leads to an increase in production and total supply of corn, increasing from 14.83 billion bushels to 15.34 billion bushels. Soybean production increases from 4.0 billion bushels to 4.1 billion bushels as shown in Table 4.

Corn prices subsequently decline by -9.1 percent to an average price of $3.29 per bushel, down from $3.62 per bushel in the Without Pennycress Scenario (Table 5). The price of soybeans remains relatively flat with an average price of $9.12 per bushel in the Without Pennycress solution and $8.88 per bushel in the With Pennycress solution. Despite the estimated decrease in corn prices, net farm income increased by $6.8 billion. Producers that grow soybeans experienced a one percent decrease in prices and a slight

Table 3: Simulated Pennycress Production by Pennycress Price (million $)

Price	Seed Supply pounds	Land Planted acres	Jet Fuel gallons
$0.00	0	0	0
$0.05	12,075.0	6.7	213.4
$0.10	23,775.0	14.2	474.2
$0.15	28,871.0	19.6	648.0
$0.20	31,266.0	22.1	723.6
$0.25	32,229.0	23.2	759.0
$0.30	32,541.0	24.1	786.5
$0.35	32,722.0	24.7	804.1
$0.40	32,871.0	25.2	818.1

Table 4: Average Annual Direct Land Use Change by Crop for the $0.20 Pennycress Price Solution. Land Planted With $0.20 Pennycress Price.

Crop	Without Pennycress million acres	Land in TraditionalCrop Rotations million acres	Acres inPennycress Rotation million acres	Total Planted Acres	Change percent
Corn	87.3	67.8	22.1	89.9	103
Sorghum	5.9	5.6		5.6	94
Oats	2.5	2.3		2.3	92
Barley	3	2.8		2.8	94
Wheat	52.1	46.5		46.5	89
Soybeans	80.9	64	22.1	86	106
Cotton	9.9	8.6		8.6	86
Rice	2.9	2.7		2.7	94
Hay	56.8	56.7		56.7	100
Pennycress	0	44.2		44.2	
Total	301.3			301.2	

Table 5: Average Price Over 2016-2039 for the Baseline and Pennycress Equal to $0.20 per Pound Solution.

Crop	Units	Average Price $/unit Without Pennycress	With Pennycress
Corn	bushel	$3.62	$3.29
Sorghum	bushel	$3.46	$4.06
Oats	bushel	$2.15	$2.11
Barley	bushel	$4.70	$5.02
Wheat	bushel	$4.94	$5.70
Soybeans	bushel	$9.12	$8.88
Cotton	Pound	$0.67	$0.72
Rice	Hundred weight	$15.81	$17.09
Hay	Ton	$154.54	$154.54

decrease in net returns, driven primarily by flat prices and increased production. An increase in the gross returns per unit sold occurs for wheat, sorghum, barley, cotton and rice producers. Producers selling pennycress seed increase their gross returns by $5.3 billion. Overall, there is a decrease in gross returns of $3.2 billion but an increase in net returns of $6.9 billion, which is caused by the direct land use change, as well as the price changes and pennycress production.

Number of Bio-refineries and Investment and Annual Operating Costs

Given that at $0.20 per pound price is paid for pennycress, an estimated 26.3 billion pounds of pennycress seed is produced. At 38 percent oil content, 10 billion pounds of pennycress oil is produced by 43 oil extraction facilities operating at 29 million gallons per year. The oil is then shipped to 22 hydro-processing with hydrogen purchase facilities to produce 723 million gallons of jet fuel along with 533 million gallons of other fuels.

IMPLAN Results

Annual Operating Impacts Resulting from Changes in the Agricultural Sector

Change in Agricultural Operations

Agriculture impacts are split into four categories – growing the feedstock crop (Pennycress), profit – as defined here as being price minus breakeven cost, change in land use, and change in price impact. Both profit and change in price impacts are estimated by impacting proprietor's income and the other two are estimated using ABP.

Table 6 contains the direct, indirect, and induced effects for the economic metrics of employment, labor income, value added or Gross Domestic Product (GDP), and economic activity or output. The pennycress to aviation fuel impact resulting from changes in the agricultural sector are estimated to be $12.1 billion if pennycress is sold at $0.20 per pound. Much of the economic activity results from the profit made on the pennycress seed. From this economic activity, almost 42,000 jobs are created. Most of these jobs originate because of growing and selling of pennycress seed. The direct land use change and price impacts had little effect on the nation's economy.

Change as a Result of Investment in Biorefinery and Oil Extraction Facilities

Investment impacts occur because two facility types are needed. The first facility crushes the seed to provide an oil to the fuel conversion facility and the second is to develop the hydro-processing facility. To produce more than 800 million gallons of jet fuel, 22 HEFA facilities are needed and 43 oil extraction facilities are required. Each facility requires investment that has a direct impact on the nation's economic activity of over 22 and 9 million for the oil extraction and HEFA facilities, respectively. In addition, once constructed, operations require over 39 and 6.8 million for the oil extraction and HEFA facilities, respectively. To achieve capacity, more than one oil

Table 6: Estimated Economic Impacts from Changes in the Agricultural Sector.

Impact Cause	Impact Type	Employment Jobs	Labor Income	Value Added Million $	Economic Activity
Pennycress	Direct	0[a]	1,043.09	1,411.52	1,945.49
Pennycress	Indirect	3,999	260.43	430.65	859.50
Pennycress	Induced	11,313	589.95	1,038.01	1,883.69
Pennycress	Total	15,313	1,893.47	2,880.18	4,688.68
Grower Profit	Direct	0	3,105.53	3,105.53	3,105.53
Grower Profit	Indirect	0	0.00	0.00	0.00
Grower Profit	Indirect	26,541	1,380.17	2,423.35	4,397.85
Grower Profit	Total	26,541	4,485.70	5,528.88	7,503.38
Total Land Use	Direct	0	0.05	0.09	0.14
Total Land Use	Indirect	0	0.02	0.04	0.08
Total Land Use	Indirect	1	0.03	0.06	0.11
Total Land Use	Total	1	0.11	0.20	0.33
Price Impact	Direct	0	-5.64	-5.64	-5.64
Price Impact	Indirect	0	0.00	0.00	0.00
Price Impact	Indirect	-48	-2.51	-4.40	-7.98
Price Impact	Total	-48	-8.14	-10.04	-13.62
Total Ag Impact	Direct	0	4,143.04	4,511.51	5,045.53
Total Ag Impact	Indirect	3,999	260.45	430.69	859.58
Total Ag Impact	Indirect	37,806	1,967.65	3,457.02	6,273.67
Total Ag Impact	Total	41,807	6,371.14	8,399.22	12,178.78

[a] Impact on jobs is 0 because it is assumed that the same individuals than planted the corn and soybeans plant and harvest the pennycress.

extraction facility are required for each hydro-processing facility. The investments for each of these facilities are presented in Appendix Tables A.2 and A.3. To provide sufficient capacity to supply 800 plus gallons of jet fuel, a one-time economic activity increase within the country of an estimated $2.5 billion for oil extraction facilities and $553 million for the hydro-processing facilities is (Table 7). Over 13.7 and 2.8 thousand jobs would be created in constructing the oil extraction facilities and hydro-processing facilities, respectively. An estimated $1.5 billion would be added to the GDP.

Annual Operating Impacts as a Result of Converting Pennycress Seed to Jet Fuel

Annually, approximately an estimated $6.5 billion is added to the economy through operations of both the oil extraction and hydro-

Table 7: One Time Economic Impacts as a Result of Investing in 22 Conversion and 43 Oil Extraction Facilities.

Impact Cause	Type of Effect	Employment Jobs	Labor Income	Value Added Million $	Output
Total Oil Extraction	Direct	5,758	$406	$487	$953
Total Oil Extraction	Indirect	2,726	$192	$321	$693
Total Oil Extraction	Indirect	5,233	$273	$480	$871
Total Oil Extraction	Total	13,713	$871	$1,288	$2,517
Total Conversion	Direct	977	$78	$88	$198
Total Conversion	Indirect	724	$51	$82	$166
Total Conversion	Indirect	1,131	$59	$104	$188
Total Conversion	Total	2,829	$188	$274	$553
Total Investment	Direct	6,735	$485	$575	$1,151
Total Investment	Indirect	3,450	$243	$403	$859
Total Investment	Indirect	6,364	$332	$584	$1,059
Total Investment	Total	16,542	$1,060	$1,562	$3,070

processing facility (Table 8). In addition, 24 thousand jobs are added. However, of the $6.5 billion, $2.8 billion results from the RIN, which is received for both the jet and diesel fuel. The estimated direct is $1.1 billion, which is an induced effect since it is assumed to be spent as proprietor income.

Total Economic Impacts to the Nation's Economy

Almost $19 billion would be added to the nation's economy, along with the creation of nearly 66,000 jobs (Table 9). This industry would add $12.6 billion to the GDP with $9.4 billion in labor income.

Discussion

Partial equilibrium simulation results from POLYSYS suggest that pennycress has the potential to supply approximately 800-million-gallons per year to the aviation fuel industry. The estimated economic impact of this industry has the potential to increase national economic activity by almost $19 billion and add 66,000 jobs. Many of these jobs will occur in rural areas. Adding value to pennycress seed by converting the oil into biofuel can enhance rural America. Transportation sector analysis is lacking in this analysis because it is not yet known where these oil extraction and hydro-processing facilities will be located, plus the transportation mode to move seed to oil extraction facilities and then oil to the hydro-processing facilities is unknown and therefore not included in the economic impact analysis.

The estimated results are also conservative based on current projections of corn and soybean prices, yield assumptions used and an imposed 6.5 percent soybean reduction. However, previous research has shown that subsequent years of pennycress production can actually improve soybean yields because of the benefits of a cover crop [19]. The model does not account for soil or other environmental benefits through the adoption of a cover crop in corn and soybean rotations. This limitation is acknowledged and left for future research. Another limitation is the use of current projections of commodity prices. As projections are updated, the effect of rising or falling prices in corn, grain sorghum, oats, barley, wheat, soybean, cotton and rice will alter the results. If future prices of corn and soybean rise, the supply of pennycress would rise as producers look to meet market demands of corn and soybean. Furthermore, the maximum yield potential is assumed at 1,600 pounds per acre for pennycress. For the regions that come into production, average yields are approximately 1,200 pounds per acre. However, previous agronomic research has found yield to be as high as 2,200 pounds per acre. Genetic research into this crop is also ongoing. Pennycress shares a similar genetic structure with *Arabidopsis*. The large body of research around *Arabidopsis* may allow for rapid advances in pennycress genetic varieties with improved yield and other desirable characteristics [17].

Table 8: Direct, Indirect, and Induced Annual Effects when Converting Pennycress Seed to Jet Fuel.

Impact Cause	Effect Type	Employment Jobs	Labor Income	Value Added Million $	Output
Oil Extraction Facility	Direct	1,208	$459	$499	$656
Oil Extraction Facility	Indirect	873	$63	$128	$238
Oil Extraction Facility	Induced	4,429	$231	$405	$735
Oil Extraction Facility	Total	6,510	$753	$1,033	$1,630
Conversion Facility	Direct	2,233	$261	$485	$896
Conversion Facility	Indirect	1,850	$147	$286	$574
Conversion Facility	Induced	3,544	$185	$325	$590
Conversion Facility	Total	7,627	$593	$1,096	$2,059
RIN Impacts	Direct	0	$1,156	$1,156	$1,156
RIN Impacts	Indirect	0	$0	$0	$0
RIN Impacts	Induced	9,878	$514	$902	$1,637
RIN Impacts	Total	9,878	$1,669	$2,058	$2,793
Total Conversion Facility	Direct	3,441	$1,877	$2,140	$2,708
Total Conversion Facility	Indirect	2,723	$209	$415	$812
Total Conversion Facility	Induced	17,851	$929	$1,632	$2,962
Total Conversion Facility	Total	24,016	$3,015	$4,187	$6,482

Table 9: Estimated Total Economic Impacts for the Oil to Jet Fuel Pathway Using Pennycress as a Feedstock and Hydro-Processing as the Conversion.

Impact Cause	Effect Type	Employment Jobs	Labor Income	Value Added Million $	Output
Total Impacts	Direct	3,442	$6,020	$6,651	$7,754
Total Impacts	Indirect	6,723	$470	$845	$1,671
Total Impacts	Induced	55,658	$2,897	$5,089	$9,236
Total Impacts	Total	65,823	$9,386	$12,586	$18,661

The oil and gas industry pays RINs to alternative or renewable fuel industries, which amounts to a transfer between regions in the United States. In this analysis, the impacts resulting from payment of RINs are not included. If included, negative impacts would likely be similar to positive impacts but in different locations within the U.S.

Finally, the POLYSYS solutions are based on USDA projections. In creating the POLYSYS Baseline to match USDA's, in some areas crops are planted that are less profitable than other crops. When this occurs, adjustments are made to the model so that regional production matches the baseline. This adjustment is carried through all scenarios and may impact areas that would shift. It is believed that at $0.20 per pound, and a breakeven cost of $0.06 per pound excluding opportunity and additional management costs, additional acreage would be realized once an industry is established.

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References

1. U.S. Department of Transportation, Bureau of Transportation Statistics (BTS) (2014) Air Carrier Financial Reports (Form 41 Financial Data), Schedule P-12(a) and P-6.
2. Davidson C, Newes E, Schwab A, Vimmerstedt L (2014) An Overview of Aviation Fuel Markets for Biofuels Stakeholders.
3. U.S. Department of Transportation (DOT), Federal Aviation Administration (FAA) (2015) Aviation Greenhouse Gas Emissions Reduction Plan.
4. Centre for Agriculture and Bioscience International (CABI) (2016) Thlaspi arvense (field pennycress).
5. Moser BR, Knothe G, Vaughn SF, Isbell TA (2009) Production and Evaluation of Biodiesel from Field Pennycress (Thlaspi arvense L.) Oil. *Energy & Fuels* 23: 4149-4155.
6. Honeywell UOP (2016) Honeywell Green Jet Fuel – Advanced Renewable Fuel Alternative to Traditional Jet Fuel.
7. Minnesota IMPLAN Group, Inc (1997) IMPLAN Professional Social Accounting & Impact Analysis Software: User's Guide. Stillwater, Minnesota: MIG, Inc.
8. Appell HR, Fu YC, Friedman S, Yavorksy PM, Wender I, et al. (1971) Converting Organic Wastes to Oil, a Replenishable Energy Source. Washington, D.C., U.S. Bureau of Mines.
9. U. S. Department of Agriculture (USDA), Office of the Chief Economist (2017) USDA Agricultural Projections to 2027.

10. Larson DL (2013) Soybean Planting Dates.
11. Pearlson MN (2011) A Techno-Economic and Environmental Assessment of Hydroprocessed Renewable Distillate Fuels.
12. Pearlson M, Wollersheim C, Heleman J (2013) A Techno-Economic Review of Hydroprocessed Renewable Esters and Fatty Acids for Jet Fuel Production. *Biofuels, Bioproducts and Biorefining* 7: 89-96.
13. Shumaker GA, McKissick JC, Woodruf J, Doherty BA (2014) Georgia Oilseed Initiative: Report on the Feasibility of an Oilseed Processing Facility in Georgia.
14. English B, Menard J, Yu E, Jensen K (2016) Analysis of the Impacts of a Hypothetical Scoring System for Biofuel Pathways Investment.
15. Agricultural Marketing Resource Center (AGMRC) (2015) Pennycress.
16. Fan J, Shonnard DR, Kalnes TN, Johnsen PB, Rao S, et al. (2013) A Life Cycle Assessment of Pennycress (Thlaspi arvense L.) - Derived Jet Fuel and Diesel. *Biomass and Bioenergy* 55: 87-100.
17. Sedbrook JC, Phippen WB, Marks MD (2014) New Approaches to Facilitate Rapid Domestication of a Wild Plant to an Oilseed Crop: Example Pennycress (Thlaspi arvense L.). *Plant Science* 227: 122-132.
18. Sharma N, Cram D, Huebert T, Zhou N, Parkin IA, et al. (2007) Exploiting the Wild Crucifer Thlaspi arvense to Identify Conserved and Novel Genes Expressed during a Plant's Response to Cold Stress. *Plant Molecular Biology* 63: 171-184.
19. Parker K, Phippen WB (2012) Impact of Heat Stress on Field Pennycress Seed Yield and Pollen Viability.
20. Federal Aviation Administration (2013) Aircraft Weight and Balance Handbook. Skyhorse Publishing, FAA-H-8083-1A.
21. Sims F (1999) Engineering Formulas Interactive: Conversions, Definitions, and Tables. New York, NY: Industrial Press, Inc.
22. Environmental Protection Agency (EPA) (2014) Gallons to Pounds Conversion.
23. Carlson S, Gailans S (2013) Aerial Seeding Versus Drill Seeding Cover Crops: Updated with Corn Yield Observations.