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ABSTRACT

Industrial hemp production has garnered producer attention as a potential summer crop alternative in Oklahoma. Farmers considering the inclusion of hemp, an emerging new crop, in their operations need to factor in risk and uncertainty. We conducted a risk analysis to determine the optimal allocation of land to conventional crops and hemp for a representative 1,000-acre wheat farm in northeastern Oklahoma under production and market risk. Target MOTAD (minimization of total absolute deviation) model was used to focus on downside risk and hemp market price uncertainty. Six double-cropping systems for double-cropped winter wheat were considered, including sorghum, sesame, hemp for grain, hemp for fiber, hemp for dual grain and fiber, and hemp for floral materials. Less than 4% of the 1,000-acre available land allocated to hemp for floral material and as much as 800 acres of hemp for grain and hemp for dual grain and fiber, were profit-maximizing allocations depending on the producer's tolerance for downside risk, target profit levels, control of cross-pollination, and market conditions.

KEYWORDS

industrial hemp, wheat, double crop, downside risk, Target MOTAD

1. INTRODUCTION

Industrial hemp (hereafter hemp) is a multiuse crop with applications of hemp oil, grain, fiber, and flowers. There were about 90,000[1] acres of hemp registered by state pilot programs across the United States in 2018 after the 2014 Agricultural Act[2] and the 2018 Agricultural Improvement Act[3] eased legislative barriers (Mark et al., 2020). Growing interest in hemp production since the 2014 Agricultural Act is attributed to increasing demand for products containing cannabidiol (CBD) derived from the hemp flower materials. The production of floral hemp has the greatest potential as a high-value crop. According to Hemp Benchmark (2020), 90% of survey individuals indicated they were growing hemp primarily for CBD production. Hemp fiber and grain are estimated to make up only 6% of the total hemp planted acreage (Jacobsen, 2020), but demand for hemp grain and fiber have continues to increase in the United States and globally (Allen & Whitney, 2019). In general, hemp acres on existing operations were relatively small. Over 50% of the producers responding to the Hemp Benchmark (2020) survey registered 10 or few acres, while less than 20% had 100 acres or more. Risk and uncertainty in production, market, financial, regulation, and especially legal perspective impact growers' decisions and US hemp market development (Raszap Skorbiansky et al., 2021).

Farmers considering the inclusion of hemp in their operation have limited information with which to make production decisions. Hemp is labor-intensive and costly to plant (Hemp Benchmarks, 2020); however, market demand for its various products could potentially boost returns to agricultural land under the right circumstances (Fortenbery & Bennett, 2004; Cherney & Small, 2016; Johnson, 2019; Key et al., 2019; Mark et al., 2020). Academic studies and production budgets for hemp are becoming more widely available and cover the variety of management practices required to produce grain, fiber, and floral hemp. Average yields and costs are available from hemp enterprise budgets published for some states such as Missouri, Tennessee, and Kentucky (Massey & Horner, 2020; Cui & Smith, 2020; Shepherd &

Mark, 2019). However, substantial gaps remain in the regional specificity of productivity and production costs.

As with the introduction of other novel crops, producers considering including hemp in their operation must balance the opportunity costs of adopting hemp with limited information about net returns, market prices, and yield. The uncertainty and risk of hemp yields is driven by low germination rates, misidentification of plant sex (females are preferred), contamination due to cross-pollination among different hemp varieties, exceedance of permissible delta-9 tetrahydrocannabinol (THC) content, and low CBD titration in final products (McCarty & Young, 2021; Mark et al., 2020; Small & Antle, 2003). Market prices for hemp are another source of risk. In 2019, national increases in hemp supply at the farm gate created an oversupply in the hemp market (Clawson et al., 2019). The 2019 hemp market price exhibited a price drop throughout the growing season from $3.50 to $4.50 per percent of CBD per pound of biomass in April 2019 to $1.40 to $1.81 per percent of CBD per pound of biomass in November 2019 (Hemp Benchmarks, 2020).[4] Production and price risk, in addition to capital investment for new machinery and increased labor costs, and access to processing facilities are presently obstacles that producers will grapple with in their determination of hemp's suitability in their production portfolio (Schlutternhofer & Yuan, 2017; Sterns, 2019).

The objective of this research is to determine risk-efficient and economically feasible cropping mix for a representative 1,000-acre winter wheat farm in northwestern Oklahoma. This is the first study on the introduction of hemp into rain-fed winter wheat double-cropping systems in the southern Great Plains. The dominant crop produced in the region is winter wheat. Producers typically fallow land after winter wheat harvest in May or early June, or they may choose to plant sesame or sorghum as a summer crop. No previous studies examine wheat and sesame double cropping. This research focuses on the possibility of including hemp for grain and fiber or hemp floral as a candidate for summer crops among sorghum and sesame. Target MOTAD (minimization of total absolute deviation) is used to model price and production risk and their influence on acreage allocation decisions among summer crop mix.

2. GROWING INDUSTRIAL HEMP IN OKLAHOMA

The Oklahoma Industrial Hemp Pilot Program issued grower registration for the first Oklahoma hemp crop in 2018. In that year 29 growers were registered, representing 445 planted acres and 80,000 square feet of greenhouses (ODAFF, 2021).[5] In 2019 Oklahoma registrations increased to 359 growers, representing 21,635 acres and over 343,000 square feet of greenhouses under the Oklahoma Industrial Hemp Pilot Program. The program became commercial in 2020. Registrations in 2020 were lower than in 2019, with 131 growers representing 3,885 acres and 243,670 square feet of greenhouses (ODAFF, 2021). Although no specific data on registered acres that were actually planted or harvested in Oklahoma exists, a national survey of hemp producers in 38 states indicated that 55% of the registered acres were planted, with 81% of those acres harvested (Hemp Benchmarks, 2020).

The number of registered acres is affected by production and market risk, including uninsurable crop loss risk, variable labor costs, the risk of cross-pollination contamination, and price uncertainty. THC content is a critical risk for hemp producers. The 2018 Agricultural Improvement Act, Title X, Subtitle G, legally differentiated hemp from marijuana based on THC content. Hemp must contain less than 0.3% THC on a dry weight basis. A material containing THC levels exceeding 0.3% falls back into the definition of marijuana as a Schedule I controlled substance. Production or distribution of such material can incur criminal penalties. Laws require destruction of hemp crops with THC levels exceeding the allowable limit. In 2020, producers self-reported that 9% of hemp acres did not meet THC requirement (Hemp Benchmarks, 2020).

In addition to the risk of losing crops for THC exceedance, farmers considering producing floral hemp also face the risk of contamination from nearby hemp fields. Field plot research suggests that hemp grown specifically for floral production should be isolated from hemp grown for other products to avoid cross-pollination (Small & Antle, 2003). Planting floral hemp near hemp for fiber or grain may dilute CBD titers and reduce the value of floral hemp (McCarty & Young, 2021).

The potential of cross-pollination is minimized by strategically configuring crop locations or by pursuing either hemp for floral material production or hemp for grain or fiber alone.

Multiperil crop insurance and the Noninsured Crop Disaster Assistance Program were available for hemp starting with the 2020 crop year. These risk management products do not cover crop destruction resulting from THC exceedance but programs do cover weather-related losses. Nationally, over 21,000 hemp acres were insured with federally subsidized crop insurance (USDA-RMA, 2020). This area represents a relatively small percentage of insured hemp acres compared to established row crops.

Hemp for grain, fiber, and floral materials are candidate summer crops for winter wheat farmers in northwestern Oklahoma. Oklahoma was the third-largest winter wheat–producing state in 2019 (USDA-NASS, 2020). Winter wheat is the largest crop acreage in the state. In 2020 there were 2.6 million acres of wheat harvested in Oklahoma, which amounts to 37% of the total acres harvested for all principle crops (USDA-NASS, 2020). Fallowing winter wheat cropland after harvest is a relatively common practice, but some producers have adopted double cropping due to low wheat prices and concerns over soil conservation (Farno et al., 2002).

When correctly implemented, double-cropping systems intensify row crop production, reduce economic risk, and increase profitability (Hansel et al., 2019; Patrignani et al., 2019; Rattalino Edreira et al., 2017; Borchers et al., 2014; Tsai et al., 1987; Grove, 1983). Oklahoma summer crop alternatives include soybeans, corn, grain sorghum, sesame, and canola. In the southern Great Plains, diversified crop rotations combined with alternative tillage, seeding, and weed control programs improve water retention for rain-fed operations (Patrignani et al., 2019). Harvesting two crops in a single year may also increase the likelihood of generating higher net returns per acre. Two summer crops are examined in this research: grain sorghum and sesame seed. These crops are adapted to rain-fed production systems typical of wheat operations in the southern Great Plains. Grain sorghum is profitable when grown following winter wheat (Williams et al., 2000). Oklahoma is the fourth-largest grain sorghum producer in the United States, producing 3.88% of the nation's sorghum crop. In terms of percent of US total production, grain sorghum lags behind only wheat (8.44% of US total) and rye (13.98% of US total) for Oklahoma row crops (USDA-NASS, 2020).

Another summer crop, sesame, is an alternative crop grown in Oklahoma and Texas. Couch et al. (2017) identified characteristics that make the wheat and sesame double-cropping system appealing for Oklahoma producers, including drought tolerance and nitrogen recovery. Sesame has experienced increased acreage with the development of shatter-resistant cultivars (Gloaguen et al., 2018; Couch et al., 2017). Like hemp, sesame faces production challenges for adoption and requires specialized harvesting equipment and cultivar development and management (Couch et al., 2017). Transportation, storage, and a limited number of postharvest handling facilities are also bottlenecks that complicate the adoption of sesame (Texas AgriLife Extension, 2007). Data on sesame prices and production is also limited. Sesame is oftentimes grouped into an "other oilseeds" category in published data sources.

3. METHODS AND DATA

3.1 Representative Farm

A 1,000-acre wheat farm representative of rain-fed operations in northwestern Oklahoma was considered for this study. After the winter wheat harvest, the farmer decided to plant grain sorghum, sesame, hemp for fiber, hemp for grain, hemp for both fiber and grain (hemp for dual fiber/grain hereafter), and hemp for floral material as a summer crop on harvested wheat acres. Grazing cattle on winter wheat is a common practice in Oklahoma (Epplin et al., 2000), but it was assumed that livestock were not grazed on wheat.

The six double-cropping systems are:

- *w-sorghum*: winter wheat followed by grain sorghum double crop
- *w-sesame*: winter wheat followed by sesame seed double crop
- *w-hempGrain*: winter wheat followed by hemp for grain double crop
- *w-hempFiber*: winter wheat followed by hemp for fiber double crop

- *w-hempDual*: winter wheat followed by hemp for dual grain/fiber double crop
- *w-hempFloral*: winter wheat followed by hemp for floral material double crop

3.2 Target MOTAD Model

Farmers are inclined to focus on the downside risk when considering the adoption of new technologies or novel production systems (Hardaker et al., 2004; Tauer, 1983; Menezes et al., 1980; Markowitz, 1959). Downside risks are negative deviations from the producer's lowest expected profit level (or a target profit level) obtainable from a new crop mix or technology. Risk-averse individuals find negative deviations from expected profits undesirable but tolerate upside variability represented as positive deviations above their target profit level. Low crop yields and market prices are sources of downside risk.

The Target MOTAD model is a useful method for modeling gross margin uncertainty and downside risk in planning and decision making when resource and management constraints are binding (Tauer, 1983; Watts et al., 1984). Compared with the mean-variance approach of Freund (1956) and Markowitz (1959),[6] Target MOTAD makes no distributional assumptions on net returns. Negative deviations from target profit levels are penalized, while positive deviations are desirable. Target MOTAD has been used extensively to model the effect of risk on farm decision making (Langemeier et al., 2020; Rosa et al., 2019; Patrice et al., 2018; Irimia-Vladu et al., 2004; Epplin & Al-Sakkaf, 1995; Misra & Spurlock, 1991; Rawlins & Bernardo, 1991; Novak et al., 1990; Zimet & Spreen, 1986), agricultural commodity markets (Frank et al., 1989; Curtis et al., 1987), regional economic efficiency (Harris et al., 2001), and environmental quality management (Bosch et al., 2018; Qiu et al., 1998, 2001; Teague et al.,1995).

The target MOTAD model formulation is

$$\max_{x,y \geq 0} \sum_{i=1}^{6} F_i \cdot x_i \tag{1}$$

subject to

$$\sum_{i=1}^{6} x_i \leq L \tag{2}$$

$$T - \textstyle\sum_{i=1}^{6} C_{ir} \cdot x_i \leq y_r \ \forall \ r = 1, \ldots, 100 \tag{3}$$

$$\sum_{r=1}^{100} \alpha_r \cdot y_r = \lambda \tag{4}$$

$$x_i \cdot x_j = 0 \ \forall \ i = w\text{-}hempFloral \tag{5},$$

where

Indexes
i: double-cropping options, $i = 1, \ldots, 100$
j: double-cropping options that may damage floral hemp, $j = 1, \ldots, 3$
r: state of nature, $r = 1, \ldots, 100$

Decision Variables
x_i: land allocation to double-cropping system *i* (acres)
y_r: net return deviation below target income in state of nature *r* ($)

Parameters
F_i: expected net return per acre for cultivation of the double crop *i* ($ per acre)
T: target profit level ($)
L: land availability (acre)
C_{ir}: net return per acre of cropping system *i* at the state of nature *r* ($ per acre)
α_r: the probability of state of nature *r*
λ: expected negative deviation from profit ($), varied from zero to a large number

The decision variables of this model are x_i, the land allocation among all production options are *i* and y_r, and the deviation from target profit under state of nature is *r*. The producer's objective is to maximize total expected net returns from producing a double-crop option $i = 1, \ldots, 6$ (*w-sorghum*, *w-sesame*, *w-hempGrain*, *w-hempFiber*, *w-hempDual*, and *w-hempFloral*) (Eq. 1). Total expected profit is the sum of the expected net returns per acre from each system (F_i) multipled by the cultivated area of each production option (x_i).

Producer decision making is subject to a set of constraints (Eqs. 2–5). Total land available is denoted by *L*. Land allocated to wheat or summer crops cannot exceed *L* (Eq. 2). The model assumes that the producer desires a target profit *T*. Due to variations in yield and market prices under the different states of nature, net returns from cultivated land is uncertain and may exceed or fall below the target profit. The variable y_r is the negative deviation below the target profit level (*T*) in state of nature r (Eq. 3). The third constraint ensures that the expected (average) deviations calculated using the occurrence probability in each state $r(\alpha_r)$ do not exceed λ (Eq. 4). The parameter λ is the expected deviation below the target profit level (T). The sample size of the state of nature is 100 in this study. This sample size is twice the imperative size Jones (1984) recommended to ensure solution stability in Target MOTAD analyses. We assume that all states of nature have an equally likely chance of occurring; therefore, $\alpha_r = 1/100$.

The model is successively solved by varying λ from zero to a large number, given a target profit level T. Lower values of λ correspond with a low tolerance for deviations away from the target profit level (i.e., the producer is risk-averse). As λ increases, the decision maker cares less about the deviations away from target profit levels (i.e., the producer tends toward risk neutrality). For each iteration, λ is set such that the target profit constraints (Eqs. 3–4) are unbinding, the model solution is feasible, and a profit-maximizing land allocation plan is obtained.

The last constraint (Eq. 5) ensures that the production of hemp for grain and fiber double-cropped with winter wheat ($j = 1, \dots, 3$) (*w-hempGrain*, *w-hempFiber*, and *w-hempDual*) does not occur when hemp for floral is produced (i = *w-hempFloral*) in this representative farm. In other words, any option in j and i are exclusively planted. The farmer cannot grow floral hemp next to hemp planted for grain, fiber, or both because the latter three crops could dilute floral hemp's CBD titer. This constraint could be removed if land parcels are not adjacent to each other and the areas of floral hemp could be effectively isolated from other hemp cultivars. We investigated both of these scenarios.

3.3 DATA AND SCENARIOS

For each state of nature r and double-cropping system i, net returns per acre are the revenue per acre ($yield_{ir} \times price_{ir}$) less the per acre production cost ($cost_i$) (Eq. 6). Because each i is a winter wheat and summer crop double-cropping system, the revenue and costs are a total of winter wheat and the summer crop of choice. For example, if i = *w-sorghum* and for $r = 1, \dots, 100$, the net returns of i (C_{ir}) is the sum of wheat revenue and sorghum revenue minus the sum of wheat and sorghum production costs.

$$C_{ir} = yield_{ir} \times price_{ir} - cost_i \qquad \forall\, r = 1, \dots, 100,\ i = 1, \dots, 6 \tag{6}$$

The expected (average) net returns per acre of cropping system i (F_i in Eq.1) is calculated using Eq. (7):

$$F_i = \frac{1}{100}\sum_{r=1}^{100} C_{ir} \tag{7}$$

Stochastic variables are crop yields and wheat, sorghum, and sesame prices. Crop yields and prices of wheat, sorghum, and sesame samples were simulated using the stochastic simulation software SIMETAR to calculate net returns per acre (C_{ir}) for each state of nature (Richardson et al., 2006). SIMETAR allows the user to define distributions for random variables that can be used to simulate a desired sample of size. Crop production costs per acre and hemp product prices were not stochastic. The following sections describe the procedure and data that were used to define yield and price distribution, production costs, and hemp price scenarios.

3.3.1 Crop Yields

Historical yields on wheat, sorghum, and sesame seed were used to generate the triangular distribution parameters minimum, maximum, and most likely (on average) (Table 1). A triangular distribution for crop yields was used in the stochastic simulation for two reasons. First, the actual distributions of sesame and hemp yields were difficult to obtain because they are relatively new crop alternatives. Information does exist on minimum, maximum, and most likely yields for these crops, all parameters of the triangular distribution. Second, triangular distribution is a suitable tool for simulating dryland crop yield (North, 1981; Dixon et al., 1989).

Wheat and sorghum yields from 1970 to 2019 were obtained from USDA-NASS (2020). The distribution parameters for sesame yield was developed based on plot yield data published by SESACO (Langham et al., 2008), the largest sesame company operating in Oklahoma and Texas.

Historical yield data for hemp is limited, and no data exists for Oklahoma. Hemp yield data from

Table 1. Crop Yield and Commodity Price Distribution Parameters

Crop	Unit	Minimum	Maximum	Mean[d]
Conventional	Yield			
Wheat	bushel per acre	17	40	29
Sorghum	bushel per acre	21	60	45
Sesame	lbs per acre	392	1,200	650
	Price			
Wheat	$ per bushel	3.71	7.72	5.00
Sorghum	$ per bushel	2.49	6.85	3.57
Sesame	$ per lb	0.29	0.43	0.35
Hemp	Yield[c]			
Grain	lbs per acre	0	1,050	525
Fiber	tons per acre	0	4.05	8.1
Hemp dual : Grain[a]	lbs per acre	0	910	455
Hemp dual: Fiber[b]	tons per acre	0	3.9	1.95
Floral	lbs per acre	0	3,000	1,519.7

a. Hemp grain yield from hemp dual system (i.e., hemp for both grain and fiber).
b. Hemp fiber yield from hemp dual system (i.e., hemp for both grain and fiber).
c. Hemp crop yield becomes zero when the crop exceeds mandated THC levels.
d. We used mean as the most likely of the triangular distribution.

neighboring states and surveys were used to determine minimum, maximum, and most likely hemp yield. The maximum and average yields for hemp for grain only, fiber only, and dual system (both grain and fiber) were from Colorado State University Extension (Russell et al., 2015). Maximum and average yields for floral hemp were based on a survey by Jacobsen (2020). A minimum yield of zero was assumed for all types of hemp production to reflect the consequences of THC exceedance.

3.3.2 Commodity Prices

The historical annual wheat and sorghum prices from 1970 to 2019 were obtained from USDA-NASS. Sesame seed prices were from the USDA Farm Service Agency (FSA) market year average record from 2011–2020 (USDA-FSA, 2021). There are no public prices reported for sesame before 2011. Given the limited historical price data for sesame, the triangular distribution was also used to generate a price distribution for the crop. Commodity prices were inflated to 2019 dollars using the implicit gross domestic product price deflator (Organisation for Economic Co-operation and Development, n.d.). The inflated prices were then detrended following procedures suggested by Pelletier (2002). The triangular distribution parameters (minimum, maximum, and average) of these three commodity prices were generated based on the inflated and detrended series (see Table 1).

Hemp grain, fiber, and floral prices were not simulated, given the limited number of observations in the United States. Hemp prices were varied from 2019 level (i.e., "Base" price scenario) to low and high levels. In 2019, the national average price for hemp products was $0.35 per pound for grain, $125 per ton for fiber, and $2 per percent of CBD per pound for floral (Hemp Benchmarks, 2019). The low level ("Low") price scenario is 25% less than the 2019 level, while the high level ("High") price scenario is 25% higher than the 2019 level (Table 2).

3.3.3 Production Costs

The average of 2015–2019 Oklahoma wheat and sorghum production costs were developed using

Table 2. Industrial Hemp Commodity Price Scenarios

		Price Scenarios		
Hemp Commodity	Unit	Low	Base	High
Grain	$ per lb	0.45	0.60	0.75
Fiber	$ per ton	93.75	125.00	156.30
Floral	$ per %CBD per lb	1.50	2.00	2.50

Table 3. Production Costs

	Production Cost ($ per acre)					
Crop	Fertilizer	Pesticide	Seed	Registration and Background Check[b]	Sampling Cost[b]	Other[d]
Wheat	42.91	18.89	16.14			77.84
Sorghum	29.91	32.72	9.33			62.98
Sesame	30.00	50.00	21.00			76.59
Hemp for grain	61.20		90.00	20.00	7.5	22.20
Hemp for fiber	59.90		150.00	20.00	7.5	188.85
Hemp dual[c]	90.90		120.00	20.00	7.5	190.04
Hemp for floral	102.00		7,623.00[a]	320.00	600	5,398.00

a. Hemp for floral used feminized seeds or clones.
b. These costs apply to hemp producers. Floral hemp for floral requires more testing than hemp for fiber and grain.
c. Hemp dual refers to hemp for both grain and fiber.
d. Other costs include custom hiring and rental, machinery operation costs, labor, supplies, and interests on variable costs.

Oklahoma State University Extension enterprise budgets (OSU Extension, 2020) (Table 3). Production costs of sesame were obtained from the 2019 Oklahoma State University Extension enterprise budget (OSU Extension, 2020). Hemp production costs for floral, grain, fiber, and dual grain/fiber were obtained from University of Missouri Extension enterprise budgets, assuming 10% CBD content per pound of biomass from hemp for floral material (Massey & Horner, 2020). There were also enterprise budgets available from Kentucky and Tennessee. We used Missouri's budget because of its geographic proximity to Oklahoma and similarities in double-cropping practices (Pullins et al., 1997). There are no hemp processing facilities in Oklahoma. We assume hauling costs of hemp products at a flat 0.02 $ per pound for grain, 5.56$ per ton for fiber, and 0.02$ per pound for floral material. Flat rate hauling costs for hemp grain and floral material were the same as the average sesame hauling costs in 2019 (OSU Extension, 2020). The hemp fiber hauling cost is the average hauling cost for alfalfa hay in 2019 for Oklahoma (OSU Extension, 2020).

3.3.4 Net Returns per Acre

Statistics on the net returns per acre (C_{ir}) distributions for each double-cropping system are presented in Table 4. For the Base scenario (i.e., the observed 2019 hemp price), the highest average net return of $15,978 (± $14,665, standard deviation) per acre was from the wheat and floral hemp double-crop (*w-hempFloral*) system. The lowest average net return of $31.91 ± $70 per acre was from the wheat and sorghum double-crop (*w-sorghum*) system. The wheat and hemp for grain double-crop (*w-hempGrain*) system ranked second in average net return at $101 per acre. The remaining double-cropping systems average net returns were similar, ranging between $55 per acre and $69 per acre.

Table 4. Statistics of Simulated Net Return ($ per acre) under Different Hemp Price Scenarios

Price Scenario	Double Cropping	Mean	Minimum	Maximum	Standard Deviation
Low	*w-hempGrain*	22	–260	354	124
	w-hempFiber	–72	–449	321	177
	w-hempDual	–63	–442	209	137
	w-hempFloral	8,465	–14,056	35,392	10,994
Base	*w-sorghum*[a]	32	–120	215	70
	w-sesame[a]	69	–96	292	90
	w-hempGrain	101	–249	522	161
	w-hempFiber	55	–449	592	238
	w-hempDual	67	–442	432	180
	w-hempFloral	15,979	–14,056	51,916	14,665
High	*w-hempGrain*	180	–247	689	198
	w-hempFiber	182	–449	863	299
	w-hempDual	196	–442	663	223
	w-hempFloral	23,493	–14,056	68,440	18,336

a. Sorghum and sesame seed prices were kept the same as the Base, Low, and High hemp price scenarios.

Floral hemp production after winter wheat (*w-hempFloral*) has the highest return of any system, even when calculated using the Low and High hemp price. However, this system generated the lowest minimum net return and the largest standard deviations. This variability aligns with anecdotal evidence provided by hemp producers. Low hemp fiber and hemp grain prices could result in negative average net returns when fields are planted to wheat followed by hemp for fiber (*w-hempFiber*) and when wheat is followed by hemp for dual grain/fiber (*w-hempDual*). The wheat and sorghum double-crop system (*w-sorghum*) has the lowest standard deviation in net returns compared to the other alternatives.

3.4 Target Profit

Based on the current land cash rent value for Oklahoma (Sahs, 2019), producers could rent land under a cash rent agreement for $30 per acre. Therefore, $30,000 was considered a reasonable target profit (T in Eq. 3) for 1,000 acres of dryland farm acres. Similarly, a lower but also reasonable target profit of $15,000 for 1,000 acres of land was used as a second target profit scenario. This value is based on the average $15 per acre rent a producer could receive by enrolling land in the Conservation Reserve Program (USDA-FSA, 2020).

4. RESULTS

Solutions were generated for each hemp price scenario under two target profit levels (T in Eq. 3), $15,000 and $30,000. The deviation from expected profits, λ (Eq. 4), was incrementally increased to determine land allocation among the cropping systems that maximizes the producer's total expected profit, subject to constraints on available land and other constraints.

Tables 5 (target profit = $15,000) and 6 (target profit = $3,000) present the expected deviation levels and risk-efficient land allocation decisions for the cropping systems, assuming that floral hemp could be grown alongside hemp for grain and fiber in this farm (without Eq. 5). In this case, cross-pollination can be avoided if floral hemp is grown on land parcels located far enough from parcels where hemp for fiber and grain grows. Optimal land allocations indicate a preference for planting hemp for grain (*w-hempGrain*) and floral hemp (*w-hempFloral*) for all hemp price scenarios so long as the expected deviation from the targeted profit level ($15,000) is $4,800 or higher. The production

Table 5. Land Allocation Solutions under Selected Expected Deviation (Target Profit = $15,000, *without* Cross-Pollination Control)

Expected Deviation ($) (λ)	Double Cropping	Price Scenarios		
		Low	Base	High
4,800	*w-sorghum*	86	523	
	w-sesame	142	25	
	w-hempGrain	8	442	750
	w-hempFiber			
	w-hempDual			230
	w-hempFloral	1	10	20
4,850	*w-sorghum*	153	524	
	w-sesame	166	20	
	w-hempGrain	8	445	752
	w-hempFiber		1	
	w-hempDual			228
	w-hempFloral	2	10	20
5,020	*w-sorghum*	162	524	
	w-sesame	213		
	w-hempGrain	8	456	757
	w-hempFiber		10	
	w-hempDual			222
	w-hempFloral	2	11	21
5,200	*w-sorghum*	168	525	
	w-sesame	241		
	w-hempGrain	11	465	763
	w-hempFiber			
	w-hempDual			216
	w-hempFloral	2	11	21
8,050	*w-sorghum*	248	230	
	w-sesame	746		
	w-hempGrain	1	755	884
	w-hempFiber			
	w-hempDual			89
	w-hempFloral	5	15	27

Table 6. Land Allocation Solutions under Selected Expected Deviation (Target Profit = $30,000, *without* Cross-Pollination Control)

Expected Deviation ($) (λ)	Double Cropping	Price Scenarios		
		Low	Base	High
9,590	*w-sorghum*	160	161	
	w-sesame	276	0	
	w-hempGrain	20	822	822
	w-hempFiber		2	
	w-hempDual			149
	w-hempFloral	3	15	28
9,600	*w-sorghum*	172	160	
	w-sesame	284		
	w-hempGrain	16	823	822
	w-hempFiber		2	
	w-hempDual			149
	w-hempFloral	3	15	28
9,800	*w-sorghum*	314	134	
	w-sesame	349		
	w-hempGrain	25	846	824
	w-hempFiber		6	
	w-hempDual			148
	w-hempFloral	4	15	29
9,990	*w-sorghum*	321	110	
	w-sesame	409		
	w-hempGrain	19	866	825
	w-hempFiber		9	
	w-hempDual			146
	w-hempFloral	4	15	29
11,220	*w-sorghum*	366		
	w-sesame	611		
	w-hempGrain	17	895	832
	w-hempFiber		88	
	w-hempDual			137
	w-hempFloral	6	17	31

of hemp for dual grain/fiber (*w-hempDual*) entered the solution only when fiber and grain hemp prices were 25% above the 2019 price. When hemp prices were at their reported 2019 level and 25% below the base, most of the 1,000 acres was allocated to grain sorghum and sesame production. Only a fraction of the 1,000 acres was allocated to produce hemp for grain (*w-hempGrain*) and floral hemp (*w-hempFloral*) because of the risks associated with the production of these novel crops.

When the hemp price was 25% below the 2019 price and the expected deviations (λ) from target profits was lower than \$8,050 (downside risk), portions of the 1,000-acre parcel were idled (see Table 5). In this case, the producer is better off fallowing portions of the parcel and setting aside a few acres for wheat and floral hemp production. All of the 1,000-acre parcel is cultivated after increasing the expected deviation from target profit to \$8,050. In this case, most of the acres are allocated to sorghum and sesame production, with a limited number of acres dedicated to hemp production (one acre to hemp for grain and five acres to floral hemp production).

Under the High price scenario (hemp price 25% above the 2019 price), acres allocated to floral hemp nearly doubled to around 20 acres compared to the Base hemp price scenario. The rest of the parcel was allocated to hemp for wheat and hemp for dual grain/fiber. Returns from all hemp production benefited from higher market prices when hemp crops were successful, but hemp for grain and fiber generated lower negative net returns per acre when crops failed (zero yields). Hemp for grain and fiber production are therefore comparatively low-risk choices in meeting the expected deviation constraint.

When the target profit level is \$30,000, the expected deviation (λ) needed to be set to \$9,590 or higher to obtain feasible solutions for all three hemp price scenarios (see Table 6). The solution generated similar land allocation patterns compared with the target profit level of \$15,000, with up to 29 acres allocated to floral hemp when the price was high and the expected deviation was set to \$9,990. This result suggests that producers with higher profit targets and a relatively high tolerance for downside risk will only allocate a few acres, not more than 4% of the 1,000 acres to produce floral hemp. If the market prices for hemp fiber and grains exceeded the 2019 price by 25%, the producer allocated more than 800 acres to hemp for grain and 100 acres to produce hemp dual grain/fiber.

When floral hemp could not be produced with other types of hemp (with Eq. 5), the optimal land allocation solution was to produce floral hemp in addition to grain sorghum and sesame seed to meet the expected deviations at both target profits (Table 7). At the target profit of \$15,000 and an expected deviation of \$4,820, 10 acres of hemp for floral material were produced when the floral hemp price was 25% higher than the 2019 price, compared with only 2 and 4 acres allocated to floral hemp production under the low and baseline price scenarios, respectively. As expected deviations from target profits increased, more land was allocated to floral hemp production. However, less than 20 acres were allocated to floral hemp when the hemp price was high and expected deviation

Table 7. Land Allocation Solutions under Selected Expected Deviation (Both Target Profits and *with* Cross-Pollination Control)

Target Profit = \$15,000					Target Profit = \$30,000				
Expected Deviation (\$) (λ)	Double Crop ID	Price Scenarios Low	Base	High	Expected Deviation (\$) (λ)	Double Crop ID	Price Scenarios Low	Base	High
4,820	*w-sorghum*	103	397	791	9,630	*w-sorghum*	188	495	776
	w-sesame	135	599	200		*w-sesame*	263	496	210
	w-hempFloral	2	4	10		*w-hempFloral*	3	9	14
8,070	*w-sorghum*	247	658	775	11,730	*w-sorghum*	294	579	803
	w-sesame	748	331	211		*w-sesame*	700	408	180
	w-hempFloral	5	10	14		*w-hempFloral*	6	12	17
12,240	*w-sorghum*		630	756	15,170	*w-sorghum*		483	843
	w-sesame	991	355	225		*w-sesame*	991	502	136
	w-hempFloral	9	15	19		*w-hempFloral*	9	16	21

from target profit reached $12,240. Similar patterns are evident when the target profit is $30,000. Hemp for grain, fiber, and dual grain/fiber did not enter into the solution because of their relatively low net returns compared with production of floral hemp, despite the fact that nonfloral hemp production generated less downside risk.

There are trade-offs between the total expected profit and the downside risk as defined by expected deviation (Figure 1). Total expected profits were the objective values that the model maximized (Eq. 1) subject to a profit target, an expected deviation from target profit, and the other constraints. The total expected profits exhibited an upward trend as the expected deviation was increased. This result suggests that a producer with a higher tolerance for downside risk may also experience higher expected profit to land. To obtain the same level of total expected profit, a larger expected deviation was required when floral hemp had to be isolated from grain and fiber hemp. Both the baseline and high hemp prices generate higher expected profit levels when hemp crops were adopted.

5. CONCLUSION

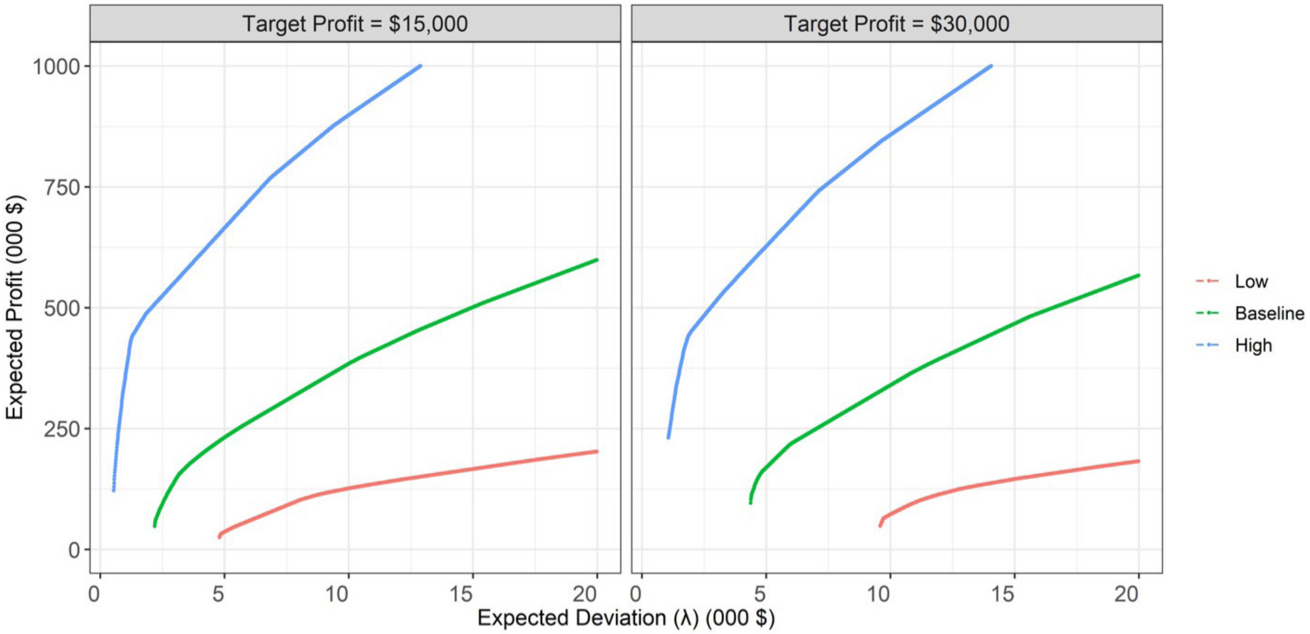
Oklahoma producers considering hemp as a summer crop face the decision of whether to try hemp and also how many acres to plant and which type of hemp they should produce. For a new crop, conventional wisdom would say to start small and build up. Low prices for conventional crop commodities up to late 2020 made large-scale hemp production tempting for some producers. Few states have tailored enterprise budgets for hemp due to limited publicly available variety trial data. No production costs have been collected in Oklahoma up to this point, and no cultivar performance data were available for hemp grown in the state. This research provides preliminary decision-making information for winter wheat growers considering the adoption of hemp.

A representative farm of 1,000 dryland wheat acres in Oklahoma was evaluated for six double-crop options. The conventional production systems were a wheat-grain–sorghum and wheat-sesame double crop. These options were compared to winter wheat followed by hemp for fiber, grain, dual fiber/grain, and floral production. Land allocation to these systems was determined using the Target MOTAD approach, an optimization model that penalizes downside variability around a target profit. Results suggest that the upside potential of hemp appears to be justified for producers who are willing to take and endure high levels of downside risk to achieve higher expected profit from the land. Land allocated to different hemp varieties mainly depended on hemp's product market prices and whether cross-pollination control was necessary.

The expansion of hemp production in Oklahoma faces many challenges. Results suggest that conventional wisdom still holds; starting small reduces exposure to risk when adopting crops in emerging markets. The simulated farm maximized profit by allocating a limited amount of land to industrial hemp production because of potential price changes and the large downside risk inherent from possible crop failure without insurance protection. Consideration of cross-pollination control could dampen the expected profit level by reducing crop options. In many cases, hemp was diversified with other known row crop options for double cropping. Very small numbers of acres in the production of floral hemp appear in the solutions because of its yield volatility as compared to the high cost of production; however, floral hemp generated the highest expected net returns per acre. Remaining acres were planted in grain sorghum or sesame, a diversification that helps to offset risk.

This research focused on hemp grown outdoors as a field crop, exposing those crops to environmental stressors that could increase THC levels and reduce yields. Production in greenhouse environments should be evaluated separately and compared against existing horticultural alternatives in Oklahoma. Future research on hemp grown as a field crop could include data from actual yields in different areas of the state from either producer surveys or field trials. Transportation costs and processor location may be influencing results for both hemp fiber and hemp grain production. As markets mature, this analysis may need to be repeated under different transportation cost levels.

Finally, contracting with processors may help offset downside risk. Improvements in state data may also help producers and hemp processors craft mutually beneficial contracts. Insurance products could also be expanded for hemp production. If processing capacity and hemp contract opportunities increase and the hemp markets mature, *Without* Cross-Pollination Control



With Cross-Pollination Control

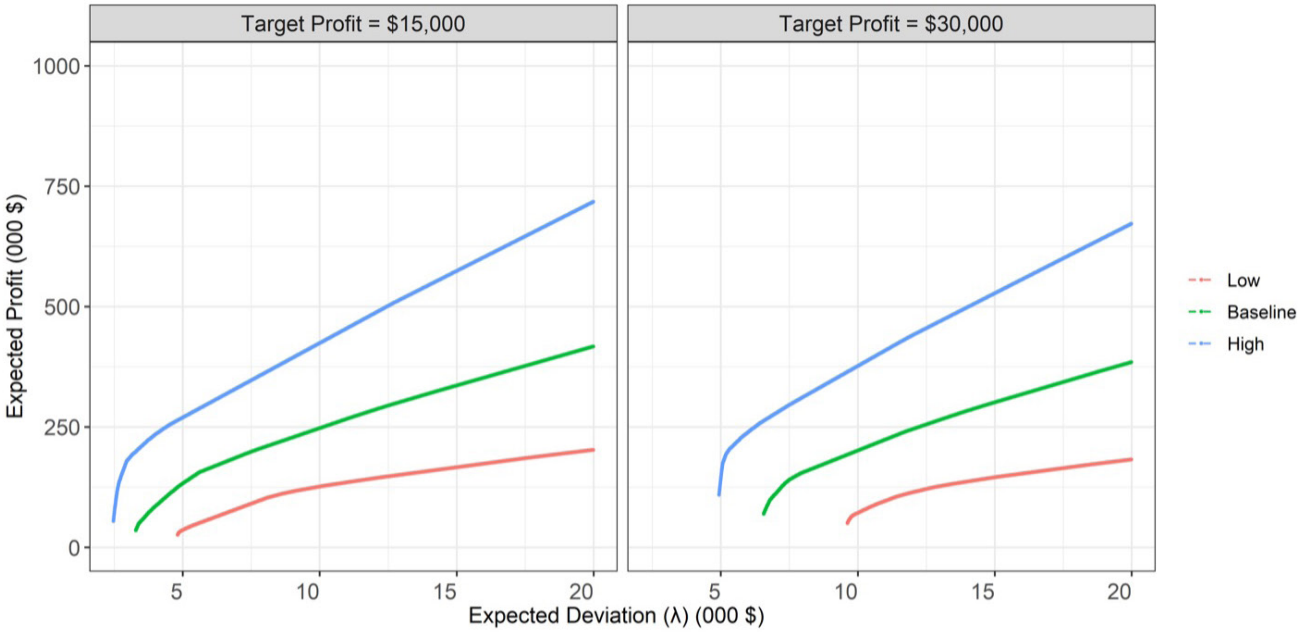


Figure 1. Trade-offs between Expected Profit and Expected Deviation

Note: Annual net returns of (A) spring-calving beef cow-calf herds grazing 30% bermudagrass/70% fescue (spring BG30), 30% switchgrass/70% fescue (spring SG30), and 100% fescue for 40-ha forage systems (spring TF100) and (B) fall-calving beef cow-calf herds grazing 30% bermudagrass/70% fescue (fall BG30), 30% switchgrass/70% fescue (fall SG30), and 100% fescue for 40-ha forage systems (fall TF100) across varying average annual rainfall (%) levels, with all other independent variables held constant at their means.

industrial hemp may find a place in Oklahoma's crop production portfolio. However, the risk is currently considerable, and producers should carefully consider those risks before investing in this fledgling market.

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NOTES

1. Actual planted acreage was likely lower than 90,000 acres that was based on state pilot program data by the USDA-ERS. The same report cited a third source (www.votehemp.com) that estimated actual planted acres to be approximately 70% of registered acres in that period.

2. The Agricultural Act, 2014, https://www.agriculture.senate.gov/imo/media/doc/Agricultural%20Act%20of%202014.pdf.

3. The Agricultural Improvement Act, 2018, https://docs.house.gov/billsthisweek/20181210/CRPT-115hrpt1072.pdf.

4. CBD markets are used as the price reference point since they tend to be higher valued than the hemp fiber or hemp grain markets. The hemp for floral material values are typically based on percentage of CBD content.

5. Obtained through personal communication with the Oklahoma Department of Agriculture, Food and Forestry on May 7, 2020, and updated on May 3, 2021.

6. Both Markowitz's and Freund's approaches toward risk assume that net returns are normally distributed.

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