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Hemp Production Network Effects: Are Producers Tipped Toward Suboptimal Varietal Selection by Their Neighbors?

Tanner McCarty (Utah State University) and Jeffrey Young (Murray State University)

ABSTRACT

The 2018 farm bill removed industrial hemp from the Schedule 1 Controlled Substance List. In response, states scrambled to enact hemp legislation. Some hemp flower producers report their hemp fields were cross-pollinated by a neighbor growing a different hemp cultivar. For hemp flower crops, cross-pollination reduces cannabinoid concentration levels within the flower; these concentration levels dictate flower price. We show that in a repeated game, once a sufficiently large percentage of growers decide to plant hemp fiber/seed crops, cross-pollination forces flower growers to convert to fiber/seed to avoid the negative network externality. Over time, a stable, suboptimal Nash equilibrium of reduced flower production results. The most important factor driving this tip to reduced flower production is pollen transmission rates between fields. This factor can be effectively reduced through either an auction-style quota system directed at seed and fiber cultivars or intertemporal zoning laws that dictate when a particular cultivar can be planted. As applications for hemp growing licenses swell, cross-pollination between farmers becomes increasingly likely. If left unchecked by policy, farm-level income and rural economic development will be suppressed.

KEYWORDS

hemp, cross-pollination, network effects, tipping points, negative externalities

INTRODUCTION

The 2018 farm bill removed industrial hemp (*Cannabis sativa L.*) from the Schedule 1 Controlled Substance List and reclassified it as an agricultural commodity. This federal legalization sparked public and private interest in hemp's potential to augment farmers' incomes and drive rural development in a time of low commodity prices and restricted market access for agricultural producers (Kentucky Department of Agriculture, 2018; Place, 2019a, 2019b). Expected hemp returns vary significantly based on the chosen cultivar. Floral hemp leads to the highest expected return, as opposed to seed or fiber. Flower cultivars contain high concentrations of cannabidiol (CBD), which is extracted postharvest from the flower. Budgets for CBD production estimate one ton of dried flower, with a 10% CBD concentration, is worth between $10,000 to $70,000 (Cui & Smith, 2019; Mark & Shepherd, 2019; Place, 2019a, 2019b). These prices are the result of the high CBD concentrations, achieved only from feminized unpollinated hemp crop. CBD is a high-value, nonintoxicating cannabis compound used in a host of therapeutic and beauty products. The CBD market is one of the fastest-growing markets in the United States. In 2018, the market value of CBD-containing products was estimated between $0.6 and $2 billion, and it is expected to grow to $15 billion by 2025 (Azer et al., 2019).

A field of feminized CBD hemp plants can be inadvertently pollinated from fiber hemp, grain hemp, nonfeminized CBD hemp, or even marijuana (Bourque, 2019; DeDecker, 2019). Before the 2018 farm bill, farmers who grew CBD hemp were unaffected by cross-pollination since they had no neighbors cultivating non-CBD hemp (e.g., fiber or seed). Hemp fields, regardless of the type of hemp grown, were geographically removed from the next; only research plots were legal. Since then, the number of industrial hemp producers has significantly increased. Hemp CBD growers claim cross-pollination from neighbors growing cultivars for fiber or seed production destroys the value of their flower crop. A field experiment by

Meier and Mediavilla (1998) found pollination to reduce CBD concentration levels by more than 50%. As growers continue to enter the hemp market, a CBD grower gains neighbors growing non-CBD hemp. As this concentration of non-CBD hemp growers increases, the likelihood of cross-pollination approaches certainty.

In markets where positive/negative externalities are incurred through social networks, existing equilibriums can be unstable and tip to a dramatically new state once a specific externality threshold is passed (Gladwell, 2006; Jackson & Yariv, 2006, 2007). For instance, if each CBD grower best responds given the conditions of the previous period, when the cross-pollination risk crosses a threshold, they will switch to growing non-CBD hemp. This, in turn affects their neighbors growing CBD, which will then influence those neighbors' production decision to switch from CBD to non-CBD alternatives. Eventually, a large proportion of the population could be exposed to a large negative-network externality, which would force all/most producers to grow non-CBD hemp. Without the externality, most growers would choose to grow the more profitable alternative, CBD. This means additional hemp licensing could lead to a suboptimal Nash equilibrium where higher valued CBD crops would no longer be viable due to the increased risk of cross-pollination from non-CBD crops.

The problem is, no one knows under what conditions the industrial hemp market would tip to reduced CBD production, and what the severity of the tip would be. The failure to prevent this tip could result in the loss and/or reduced viability of a multibillion-dollar agricultural industry. On the other hand, introducing unneeded legislation could raise the cost of hemp production. This paper offers two primary contributions to addressing this problem. First, we identify the marginal impact that hemp market primitives (pollen transmission rate, economic attractiveness of either crop and network structure) has in pushing the industrial hemp market toward a tip to the suboptimal, reduced-CBD Nash equilibrium. Second, we identify policies capable of targeting the hemp market primitives that have the largest impact on tipping the industry. Using the general framework developed by Jackson and Yariv (2006), we examine hemp varietal selection through the lens of negative network externalities and decision making within social networks.

Hemp markets are complex. The number of each grower's neighbors, their decisions, and the transmission rate of pollen from neighboring fields affects each grower's payoff. The social network economics literature examines how an individual agent's payoff is affected by their neighbor's actions. A subset of the social network literature, first explored by Gladwell (2006), examines how the change of actions by a small subgroup can disproportionately affect the rest of the population's outcomes. The proposition that a change in the actions of several agents can have a dramatic effect on the final equilibrium of actions followed by an entire population is referred to as tipping. The key takeaway in the tipping literature is that a change in action by a sufficiently high proportion of the population can result in a cascading response, where the rest of the population responds by changing their own actions. Thus, this social network literature is especially applicable to industrial hemp.

Jackson and Yariv (2006) developed a generalized model capable of accommodating these network externalities, tipping, and agents' best response to neighbor's actions. They use this model to examine how changes in key primitives relative to social networks affect the threshold at which tipping to a new action occurs and how much of the population subsequently adopts the new action after a tip. We apply their general model to a grower's decision to grow CBD or non-CBD hemp. Specifically, we characterize how economic and network factors affect hemp growers' expected returns for CBD and non-CBD. We then test under what conditions these hemp markets tip to new equilibriums of decreased CBD production. We subsequently identify the most important influencers of tips and discuss policy tools to shape them.

MODEL

Assume that a finite set of hemp growers can choose one of two actions: action A, grow CBD hemp, or action B, grow non-CBD hemp. The action each grower chooses affects the payout function of his/her neighbors through the network. Each individual grower i has a number of direct neighbors of a degree d_i. The percentage of individuals within this subset that have d neighbors is represented as $P(d) \geq 0$, for $d = 1, 2, \ldots, dmax$, and $\sum_{d=1}^{d\max} P(d) = 1$, where $P(d)$ represents the percentage of the population with d neighbors.

First consider action A, the default choice due to its higher expected profit. The payout grower i receives from growing crop A is a function of the expected revenue, r_{iA}, minus operating cost from choosing A, w_{iA}, minus the expected externality cost incurred through cross-pollination, $e_{iA}g(d_i)\lambda_i$ (where e_{iA} is the penalty to revenue due to reduced CBD concentrations if cross-pollination occurs). The term $g(d_i)\lambda_i$ denotes the probability of cross-pollination. Cross-pollination becomes increasingly likely as the fraction of grower i's neighbors choosing to grow B, λ_i, increases. The number of neighbors that farmer i has, d_i, also increases the probability of cross-pollination. Thus both λ_i and d_i affect how likely grower i is to experiencing externality cost e_{iA} if they choose A. Finally, a grower evaluates these expected prices, costs, and externalities through their own risk aversion characteristics leading to their own utility of crop A, U_{iA}. Grower i's payoff for choosing to grow crop A, V_{iA}, takes the form:

$$V_{iA} = U_{iA}\left(r_{iA} - w_{iA} - e_{iA}g(d_i)\lambda_i\right) \tag{1}$$

The payoff to grower i for cultivating B is independent of what their neighbors choose, since action B is unaffected by pollination. Grower i's payoff for choosing B depends only on B's revenue, r_{iB}, the operating cost, w_{iB}, and how their risk aversion shape their utility, U_{iB}. Grower i's payoff for action B, V_{iB} is defined as:

$$V_{iB} = U_{iB}\left(r_{iB} - w_{iB}\right) \tag{2}$$

A grower will switch from action A to B once he perceived benefits of B, B_{iB} outweigh the costs of B, C_{iB}. We rearrange terms to make the costs of choosing B equal to the value grower i places on the forgone private profit from choosing A, π_{iA} minus the private profit of choosing B, π_{iB}:

$$C_{iB} = U(\pi_{iB} - w_{iB}) \tag{3}$$

This means the benefit of choosing B is the expected value of the externality cost that would have been incurred had the grower chosen A. Rearranging these terms allows us to isolate the effect of the externality size and probability on individual decision making.

$$B_{iB} = U\left(e_{iA}g(d_i)\lambda_i\right) \tag{4}$$

Finally, a grower currently producing CBD hemp will switch to non-CBD hemp once their benefits outweigh their costs of doing so. This occurs when:

$$R_i = \frac{B_{iB}}{C_{iB}} \geq 1 \tag{5}$$

Equation (5) effectively captures a grower's decision to continue growing CBD or switch to non-CBD. Changes in prices, costs, or the structure of g will push individual CBD growers toward or away from non-CBD production, which in turn affects their neighbors through the network externality they experience. Due to the network's interconnectedness, changes by individuals in the network may dramatically shift the portfolio of hemp production from CBD to non-CBD alternatives.

Game Setup

At time $t = 0$, a percentage of the growers within the population of all hemp growers randomly select B, X_0. At each time point, $t > 0$ each grower responds to the distribution of other growers who chose B in period $t-1$. We assume that growers who voluntarily chose B never switch back; this ensures a stable "steady state" equilibrium result over time. This assumption greatly simplifies the problem with little loss in generality. If a grower decides to switch to B to avoid a negative externality for relatively low levels of d_i and λ_i, they would not switch back at later periods when these levels are higher. Depending on market characteristics and the initial size of X_0, the state variable X_t (percentage of growers within the network who have adopted B at time t) will either rise or fall over time until it reaches a steady state, $\overline{X}$. Once in the steady state, no agent has any incentive to switch states. The initial state X_0 enters into (5) through its implicit effect on λ_i; more initial adopters of B within the population (X_0) means that individual farmers will, on average, have a higher value of λ_i.

One of three possibilities results from the initial value of X_0. First, low levels of X_0 cause a decrease in the percentage of B adopters over time ($X_{t+1} < X_t$), and the percentage of B adopters falls until the steady state adopter percentage, $\overline{X} < X_0$. Second, high levels of X_0 trigger a tip ($X_{t+1} > X_t$), and the percentage of B adopters rapidly increases until a new equilibrium occurs where $\overline{X} > X_0$. Third, the current percentage of B adopters is maintained over time ($X_{t+1} = X_t$), and $\overline{X} = X_0$. This point is of particular importance as it triggers the tip to a new steady state. This level of X_0 that maintains balance is referred to as the tipping point. Values above cause an increase to a new higher steady state and values below drive decreased B adoption. This tipping point is denoted X_0^*. In the context of hemp production, passing the tipping point is problematic since the tip results from the negative externality costs that non-CBD producers impose on CBD producers. The result is a suboptimal Nash equilibrium.

PARAMETER ASSUMPTIONS AND NETWORK STRUCTURE

The following subsections explain the empirics associated with Equation (5) and the structure of the network through which those individual decisions permeate.

Costs of Switching to Non-CBD Hemp

As previously mentioned, the costs of switching to non-CBD hemp production is the utility grower *i* receives from private profit of growing CBD minus the private profit to growing non-CBD. CBD hemp farming is an enterprise of relatively high risk and potential returns, when compared with fiber or grain hemp production (Hanchar, 2019). For example, fiber hemp revenues are estimated to be $750–$800 per acre, which appears rather small when compared to the expected $10,000–$70,000 per acre for CBD production (Hanchar, 2019; Mark & Shepherd, 2019). The range of CBD revenue is so large due to differences in CBD prices, CBD concentration levels within the plant, and yield per acre experienced in different locations at different times.

Fiber hemp operating cost is estimated to be $390 per acre. The selling price of feminized clones necessary for achieving high CBD concentration range between $4 and $10 per individual plant, with more than a thousand planted on a single acre (Kim & Mahlberg, 1997; Meier & Mediavilla, 1998; Small & Naraine, 2016). Combined with high labor requirements, these costs contribute to an estimated yearly operating cost of around $10,000–$15,000 per acre (Hanchar, 2019; Place, 2019a, 2019b; Schaneman, 2019). CBD hemp is risky to grow; various stresses such as drought, temperature, and altitude can cause THC levels within a plant to spike (Gerlach, 2019; Place, 2019a, 2019b). If a CBD crop tests at more than 0.3% THC content, it is destroyed by drug enforcement agencies (Gerlach, 2019; Place, 2019a, 2019b). These differences in risk-return profiles imply that more risk-averse hemp growers will gravitate toward producing grain or fiber, while the less risk-averse hemp growers will gravitate toward the more profitable CBD production. The exact level of C_{iB} varies by grower.

Benefits of Switching to Non-CBD

As mentioned in the previous section, the benefit of switching to non-CBD is the utility gained from the avoided damage from cross-pollination achieved by not growing CBD, $U(e_{iA}g(d_i)\lambda_i)$. Parameter e_{iA} denotes the damage itself and $g(d_i)\lambda_i$ denotes the probability of cross-pollination. Parameter g maps the effect of d_i onto the expectation of externality damage. We specify $g(d_i) = \alpha d_i^{\beta}$ where β approximates how contagious an additional neighbor growing fiber is for cross-pollination (the marginal transmission rate). For this analysis we assume $0 \le \beta \le 1$. This means that increases in both the total number of grower *i*'s neighbors and the fraction of neighbors within a given grower *i*'s network choosing B increase the relative attractiveness of choosing non-CBD for grower *i*. This assumption captures the empirical effect cross-pollination has on CBD producers. The specification of β also ensures that there is a diminishing effect of each additional neighbor on the probability of cross-pollination. We use α as a scalar to constrain the probability of cross-pollination between 0 and 100%. Specifically, we rescaled α to ensure 100% of cross-pollination when $\lambda_0 = 1$ and 0% when $\lambda_0 = 0$, for the highest level of d considered in this analysis, $dmax = 20$. The exact level of B_{iB} is affected by current CBD prices, CBD crop yields, the reduction in CBD concentration levels incurred through cross-pollination, and grower's valuation of risk. This means B_{iB} varies by grower.

Cost-Benefit Ratios

Differences in benefits and costs across growers means there is a distribution of possible cost-benefit ratios of adopting non-CBD, $\frac{B_{iB}}{C_{iB}} = R$ within a social network. We follow Jackson and Yariv (2006) by modeling this distribution of R to be uniformly distributed on the interval 0 to R_{max}. We explore R_{max} levels on uniform distributions between 0 to $R_{max} = 10$ and uniform distributions between 0 and $R_{max} = 40$.

Structure of the Underlying Network

We follow the assumptions made by Jackson and Yariv (2006) and assume that growers interact with one another through a network with a "scale-free structure," specifically the pdf of having d neighbors, $f(d) = \frac{1}{d^{2.5}}$. This distributional assumption for neighbor degree is an appropriate characterization of the industrial hemp networks. A few areas of the United States have many individuals growing hemp in a small area. Many areas of the United States have a limited number of individuals growing hemp in a large area. Furthermore, this modeling assumption is consistent with many other social network applications such as the World Wide Web and epidemiology. Powers associated with these types of distributions often provide the best approximation of the network when they fall between 2 and 3 (Newman, 2002).

The average degree of neighbors within the population is $\overline{d}$, $\overline{d} = \left(\frac{\sum_d dP(d)}{\sum_d (P(d))}\right)$. The percentage of B adopters in a network at time t evolves following the formula in Equation 6[1]:

$$X_t = 1 - \sum_d \frac{dP(d)}{\overline{d}} \min\left[1, \frac{1}{R_{\max} g(d) X_{t-1}}\right] \quad (6)$$

RESULTS

Individual Decision Making

Due to the heterogeneity in a grower's perceived costs and benefits to switching to non-CBD and the heterogeneity in the number of neighbors a grower has, the exact threshold for individual conversion to choose non-CBD varies by farmer. From a policy perspective, the individual decision is less important than the market as a whole. However, to understand the market we must first understand what drives individual decisions. In this section, we focus results on qualitative considerations that affect all individual growers' decisions to switch to non-CBD. In the following section, we quantitatively examine the impact of changes in key market primitives on the market.

Recall that Equation (5) maps the individual decision of a hemp grower to continue growing CBD or switch to non-CBD conditional on actions by grower *i*'s neighbors. The actions taken by grower *i* this period subsequently affect the actions of their neighbors next period through their network. Taking the first order conditions of each variable in Equation (5), we recover the effect that each variable has on a grower's decision to grow CBD or non-CBD hemp. The results of these comparative statics are included in Table 1.

The results suggest that increases to private profit associated with growing CBD, π_{iA}, make a change to non-CBD less attractive, whereas increases in private profit to non-CBD make it more attractive. Put differently, if non-CBD production increases expected profitability relative to CBD production, more growers will switch to non-CBD. This outcome is expected. The larger the size of the network externality, e_i, the more attractive non-CBD becomes. In other words, the grower would have more incentive to switch to non-CBD production if cross-pollination penalized CBD levels by 60% than if it penalized CBD levels by 30%. This result reinforces the importance of genetics in selecting CBD cultivars. Some strains of CBD plants may be less affected by cross-pollination than others.

A grower producing CBD will be incentivized to switch to non-CBD as the percentage of their neighbors growing non-CBD hemp, λ_i increases. As the percentage of neighbors growing non-CBD increases, a grower will become increasingly likely to get their CBD crop cross-pollinated as they are effectively surrounded on more sides by neighbors

Table 1. Change in grower *i*'s benefit cost ratio, *R*, of switching from CBD to non-CBD production in response to changes in variables

$\frac{\partial \boldsymbol{R}}{\partial \pi_{iA}} < 0$	$\frac{\partial \boldsymbol{R}}{\partial \pi_{iB}} > 0$
$\frac{\partial \boldsymbol{R}}{\partial d_i} > 0$	$\frac{\partial \boldsymbol{R}}{\partial g} > 0$
$\frac{\partial \boldsymbol{R}}{\partial \lambda_i} > 0$	$\frac{\partial \boldsymbol{R}}{\partial e_i} > 0$

who could cross-pollinate them. The total number of neighbors, d_i, matters as well. Even if a grower is surrounded by the same acreage of neighbors growing non-CBD, cross-pollination is more likely if they have multiple small neighbors growing it than if one large neighbor is; pollination can only occur over a specific time interval. If a CBD grower plants at a sufficiently different time than their neighbor growing non-CBD hemp, then cross-pollination is less likely. The probability that at least one neighbor plants non-CBD at a problematic time increases as more neighbors are introduced (the supply of available land is assumed to be fixed).

Finally, the strength of g affects farmers' decisions to grow non-CBD. Put differently, g effectively amplifies the effect that having more neighbors and having a higher percentage of neighbors has on the probability of being cross-pollinated. If g becomes stronger from something like the average distance between neighbors decreasing, then growers will be increasingly incentivized to switch to non-CBD production.

Market Dynamics

In this section, we examine tipping thresholds and the resulting steady state under a range of key market primitives. These primitives include β values between 0 and 1, maximum degrees within a scale-free network, d_{max}, between 5 and 20, and the uniform distribution modeling benefit-cost ratios occurring between 0 and 10, and 0 and 40. Changing each of these primitives affects the percentage of initial adopters that cause a tip to increased non-CBD hemp production and the level of non-CBD hemp production that occurs after the tip. The following sections explain what each comparative static captures, why it was conducted, and the impact that changing it has on tipping points and the resulting steady state.

Transmission of Pollen

Recall that $g = \alpha d^{\beta}\lambda_0$ denotes the probability that cross-pollination occurs. We rescaled α to ensure 100% of cross-pollination when $X_0 = 1.0$ for the highest level of d considered in this analysis, $dmax = 20$, and conditional on what β is, $\alpha = \frac{1}{20^{\beta}}$. Specifying the problem in this way allows us to approximate how contagious an additional neighbor growing fiber is for cross-pollination (marginal transmission rate). The marginal transmission rate denotes how quickly one more neighbor increases the probability of cross-pollination. Exploring various transmission rates matters because there is currently only limited evidence on transmission rates for cross-pollination between fields. If pollen is highly transmittable and pollinates the majority of a neighbor's field, then a β closer to 0 is appropriate. If, however, pollen is less transmittable and/or only pollinates small pockets of a neighbor's field, then a β closer to 1.0 is appropriate. Values of β should not exceed 1.0, for this would imply an increasing marginal pollen transmission rate. Under baseline assumptions and 50% of the population having adopted fiber ($X_0 = 0.50$), going from zero to one neighbors changes the probability of cross-pollination from 0 to 50% when $\beta = 0$, and 0 to 2.5% when $\beta = 1.0$. In both specifications, the probability of cross-pollination is 100% when $d = 20$ and $X_0 = 100\%$.

Figure 1 displays the impact of pollen's marginal transmission rate, β, on tipping dynamics within a hemp network. Different lines denote different β levels. Recall that $\beta = 0$ implies high pollination transmission between fields, and $\beta = 1.0$ implies lower transmission between fields. X_0 denotes the percentage of all growers within the network who have adopted non-CBD crops at time 0. X_1 denotes the percentage of all growers within the network who have adopted non-CBD crops the following period. These curves are compared with a 45-degree line to illustrate if a trend either dies out or causes a tip to a new steady state over time. Going from left to right on the horizontal access, the first place the β curve intersects the 45-degree line is the tipping point. For a given curve, this percentage of initial adoption leads to the exact same amount of adopters the following period, $X_0 = X_1$. If X_0 is greater than this, a tip occurs and $X_1 > X_0$ which will continue until the curve intersects the 45-degree line a second time in which a new steady state is realized where once again $X_0 = X_1$ For example, our baseline assumption of $\beta = 0.50$ tips at $X_0^* = 22\%$ and a moves to steady state of $\bar{X} = 75\%$ after a tip occurs. Levels of X_0 higher than 75 percent will decrease back to the steady state of $\bar{X} = 75\%$.

The key takeaway is that transmission rate matters a great deal for both whether the hemp market

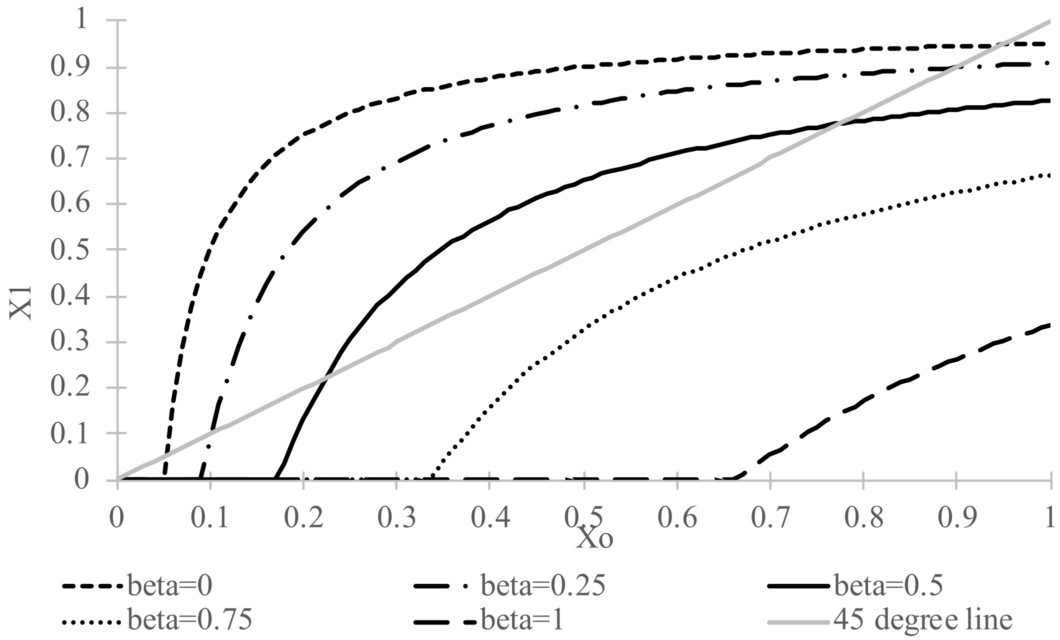

Figure 1. The impact of transmission rates on the tipping point and steady state of an industrial hemp network.

tips to non-CBD production, and if it does tip, what percentage of it grows non-CBD. This means that supporting agronomic research to accurately estimate transmission rates is paramount. It also highlights some potentially strong policy prescriptions. Finding a way to shift β from 0.50 to 0.75 is enough to go from a tipping point of roughly $X_0^* = 22\%$ and a steady state of $\overline{X} = 75\%$ of hemp crops being non-CBD to one where a tip is impossible. While policy makers cannot change the agronomics, they can affect β through the mandate of barriers such as tree rows, or intertemporally spacing when growers are allowed to plant various cultivars, which would keep reproductive maturity times staggered, therefore reducing transmission rates.

Degree of Neighbors

Degree captures the underlying structure of a given network. We assume a scale-free network where the probability density of having d neighbors is $d^{-2.5}$. This captures the empirical nature of this emerging hemp industry. A few regions of the United States have many individuals growing hemp in a small area. Many areas of the United States have a select number of individuals growing hemp in a large area. While this network structure that models central production hubs makes sense, we do not know what the maximum amount of neighbors, *dmax*, within a network is possible due to a lack of agronomic data quantifying pollen travel distance. A neighbor only counts as a neighbor if their crop is close enough to cross-pollinate another grower's crop. If pollination only can occur from adjacent fields, then a maximum of 5 neighbors in a network is reasonable. If pollination can travel farther distances, then a degree of 20 or more would be more appropriate to assume. Additionally, *dmax* is a moving target in both geography and time. Some regions in the United States grow more hemp than others. As additional farmers enter the hemp market, both *dmax* within a network and the expected degree for individual agents will increase over time.

Figure 2 captures the effect of network structure on tipping points and resulting steady states. Like Figure 1, X_0 denotes the percentage of all growers within the network who have adopted non-CBD crops at time 0. X_1 denotes the percentage of all growers within the network who have adopted non-CBD crops the following period. The curves denote different maximum values possible for degree of neighbors within a scale-free network.

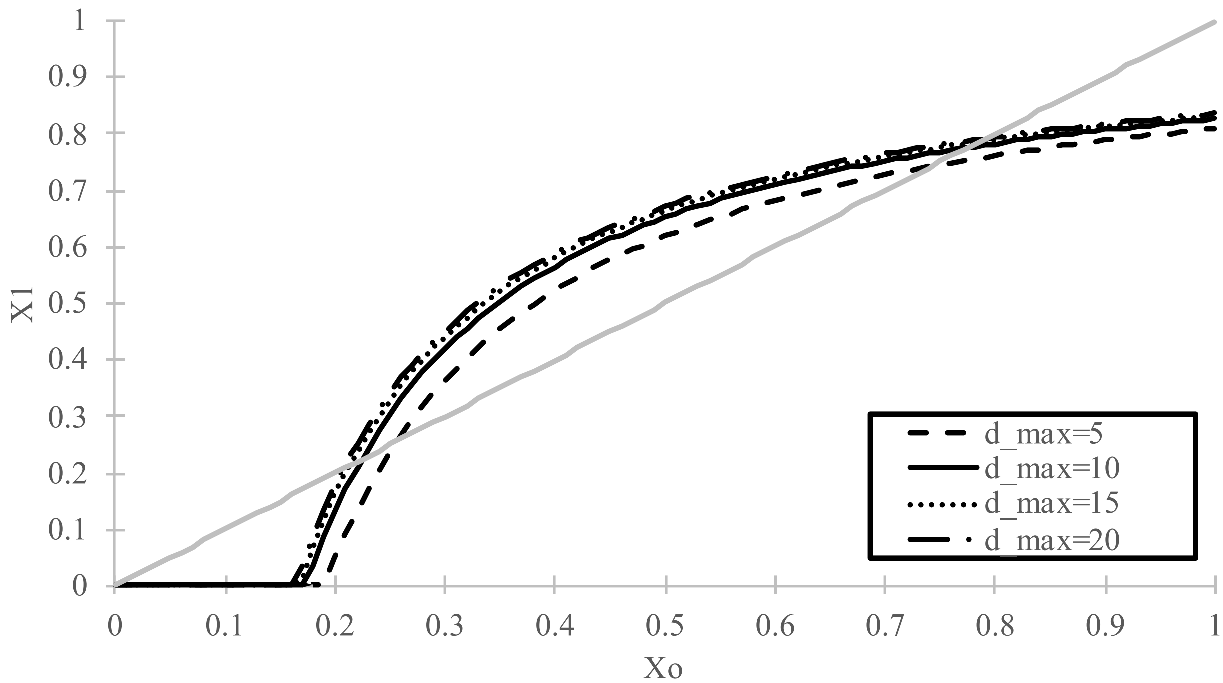

Figure 2. Tipping points versus neighbor degrees.

For example, $d_{max} = 5$ means a scale-free network with 1–5 neighbors possible and $d_{max} = 10$ means a scale-free network with 1–10 neighbors possible.

Unsurprisingly, increasing the amount of possible total neighbors within a network reduces the tipping point threshold and increases the resulting steady state after a tip. More surprising is its limited effect. Two potential explanations exist for this. The first is that under baseline assumptions of $\beta = 0.5$ transmission rates are fairly high for one additional farmer. For instance, if 50% of the population has already adopted the non-CBD crop, changing from a degree of 0 to 1 neighbor increases the probability of cross-pollination from 0% to 22%. Going from 4 neighbors to 5 in this situation increases cross-pollination from 45% to 50%. This diminishing effect means that each neighbor added to an individual grower's circle is less important than the one before. When transmission rates are lower (β is higher), d_{max} has a larger effect. The second reason for this is due to the scale-free network assumption. Higher d_{max} values have a smaller effect on the actual expected value degree. Maximum values within scale-free networks are unlikely, so increasing that maximum value does not have a large impact on tipping dynamics. Policy-wise it seems more important to lower transmission rates than it does to limit the number of growers in a vacuum. Having more growers in a region, however, necessarily decreases the average distance between fields in that region, which would ultimately increase transmission rates.

Cost-Benefit Ranges

The quotient R is the distribution of grower's benefit-cost ratio of adopting non-CBD within a network: $R = pdf(\frac{B_i}{C_i}) \epsilon (i = 1, \dots N)$, where N is the total number of growers within a network. These benefits and costs contain objective values such as price and yield that can both vary across time and region. They also contain subjective values for how a given agent values risk. A high value for $\frac{B_i}{C_i}$ implies a given grower views farming fiber relatively favorably compared to farming CBD and will switch to fiber even when pollination is unlikely. A low value for R implies a given grower views farming fiber relatively unfavorably compared to farming CBD and will switch to fiber only when cross-pollination is very likely. The distribution R for growers within the network is uniformly distributed between 0 and R_{Max}. R_{Max} is the maximum ratio possible of $\frac{B_i}{C_i}$ for all growers included in a

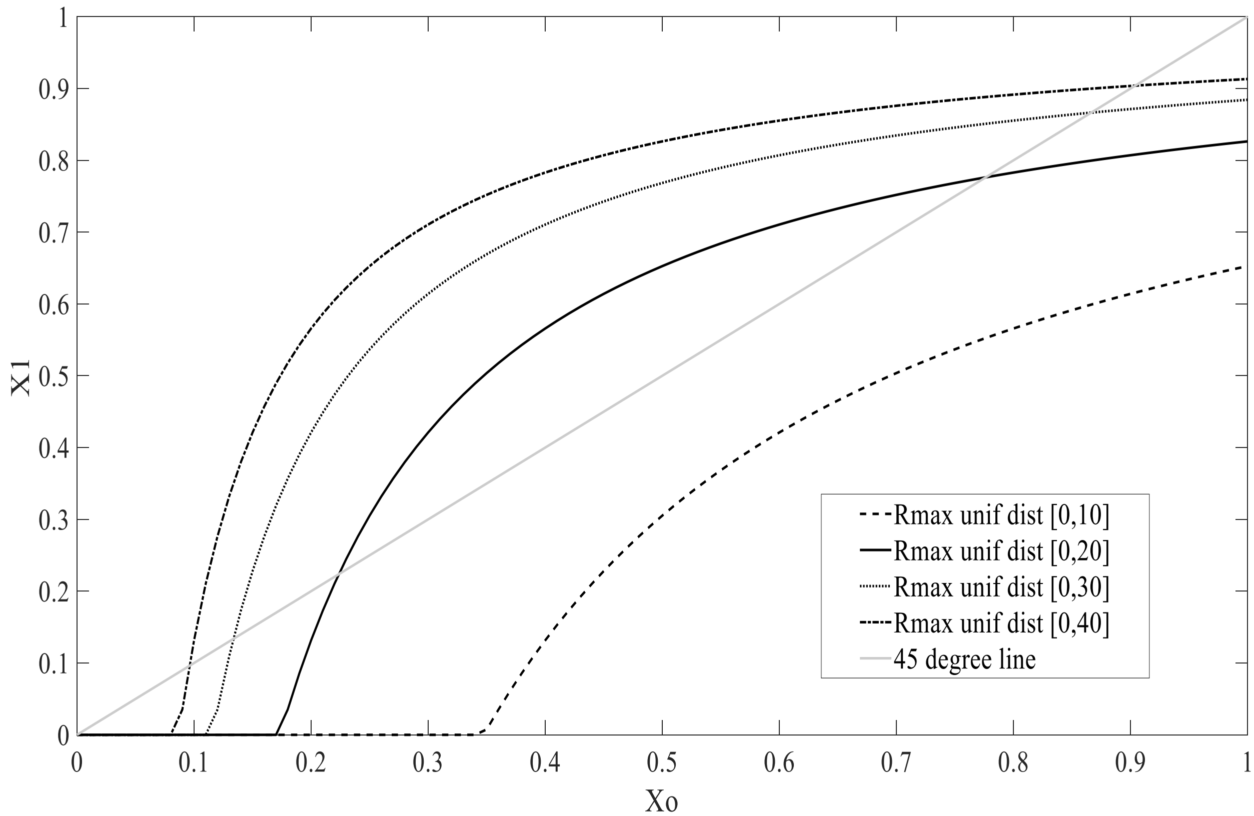

Figure 3. Tipping point and steady state for varying levels of B_{max} in the benefit-cost ratio of switching to fiber.

network. Networks with a high R_{Max} will, on average, view non-CBD farming more favorably than networks with lower R_{Max}. In a network of risk-neutral farmers and favorable expected profits for CBD versus non-CBD, relatively low R_{Max} values make sense. In a network of highly risk-adverse farmers and expected CBD profits only slightly higher than non-CBD, higher R_{Max} values make sense.

Figure 3 shows the magnitude that expected benefit cost ratios have on tipping and steady state decisions. Curves denote uniform distributional assumptions that go from 0 to R_{Max}. Higher values of R_{Max} are indicative of higher expected benefit/cost ratios of switching to non-CBD production. From Figure 3, we can observe that the more favorable growing non-CBD hemp is relative to CBD, the earlier tips occur and the higher the level of the resulting steady state. What is more surprising is how high R_{Max} must be to induce a tip under our baseline assumptions of $\beta = 0.50$ and $d_{max} = 20$. Recall that $R_i = \frac{B_i}{C_i}$ for grower i, where B_i denotes the benefit to growing non-CBD plus the avoided externality cost of not growing CBD—if the crop is cross-pollinated. However, CBD crops are not cross-pollinated with 100% certainty, which is why we include parameters $g = \alpha d^{\beta} \lambda_0$ to denote how likely cross-pollination is. A g below 100% ultimately scales down B_i. This means that as long as cross-pollination is sufficiently unlikely or the damage to cross-pollination is low, a tip is unlikely to occur. This highlights the importance of developing CBD cultivars that are resistant to cross-pollination.

CONCLUSIONS AND POLICY IMPLICATIONS

When viewing our problem through the lens of diffusion on social networks, we notice one primary problem and four potential solutions. The problem is new farmers keep entering the hemp industry. This both increases d and strengthens the effect of g, which makes producing CBD hemp less attractive. The effect of g grows as the entry of additional hemp producers within a network decreases the distance between neighbors and increases the likelihood of at least one non-CBD neighbor's crop reaching reproductive maturity at the same time as the CBD crop. This will eventually tip the industry from CBD hemp to fiber or seed hemp. Such an outcome is problematic, given that, at present, the estimated per acre revenue from CBD hemp production, absent cross-pollination, is many times the expected per acre revenue from fiber or seed production.

Policy makers could address this by capping the amount of permits available for fiber and seed and auctioning them. This would increase the cost of growing non-CBD, C_i, limit how large λ_i could become, and limit the strength g (by increasing β) since fewer hemp producers would increase the average distance between each neighbor. This policy is attractive as it simultaneously targets the primitive with the largest effect on tipping (pollen transmission rates), while making it possible to constrain the percentage of non-CBD producers below the X_0^* associated with a given level of *bmax*, *Rmax*, and β.

Additionally, legislators could require fiber and seed producers to erect natural barriers such as a row of trees. This would simultaneously increase the cost of growing fiber, C_i, and reduce the strength of g. Windbreaks and other thick crops at the border of a field were estimated to reduce maize pollen dispersal between 30% and 60% (Ushiyama et al., 2009) and may also be efficient solutions in the context of hemp. Windbreaks would limit the strength of g by making cross-pollination less likely. The advantage to windbreaks is that they would degrade externality cost without additional regulation and would enhance biodiversity in the locales that implement them. The drawback to windbreaks is that they would likely be costly to implement both in terms of planting cost and reduced acreage available for growing crops.

Agricultural zoning laws that geographically separate CBD and non-CBD production would reduce the proportion of CBD growers' neighbors growing fiber λ_i, and the strength of g. The strength of g is reduced by increasing distance between CBD producers and their non-CBD producing neighbors. Cross-pollination from a non-CBD producer is more likely if they are ¼ mile away than if they are 2 miles away. This could be problematic as it would not allow growers to self-select into what crop they would prefer to grow, since their land is in a fixed location.

Temporal zoning laws that separate when CBD and fiber planting occur could reduce the probability of the negative externality occurring by staggering plant reproductive cycles. Temporal zoning laws reduce the strength of g which ultimately diminishes the effect of increases in d_i or λ_i. Temporal zoning is an attractive possibility as it limits the probability of cross-pollination without passing on any large cost to growers. Most growers currently grow hemp as a supplemental crop and not their sole crop. The thought is that farmers could redirect their time when they are not allowed to plant hemp to get their other crops established, freeing up time for when they can legally plant hemp. This would be less true if they were only growing hemp crops. These alternative policies can make the switch to non-CBD less attractive, subsequently pushing the hemp industry away from the tipping point and protecting CBD producers.

The hemp industry is currently developing in a way that would encourage a tip to zero CBD (or near zero) production. General increases in the number of hemp farmers—and specifically increases in grain and fiber hemp farmers—contribute to increasing the negative network externality passed on to CBD growers. In the absence of policy to correct this, the industrial hemp market may tip to a new suboptimal Nash equilibrium where only/mostly fiber and grain hemp are grown, thereby decreasing farm-level income. Of the policy prescriptions considered, an auction for non-CBD production and intertemporal spacing appear to be the two with the most potential for preventing a tip to high non-CBD production. Auctioning rights to producing a good with a negative externality is a classic way of efficiently addressing the externality as it establishes property rights on the environmental amenity being degraded, in this case pollen levels in the air. Non-CBD producers would be forced to internalize the cost of their externality by paying for the right to emit pollen. This policy would increase distance between neighbors (decrease the strength of g by increasing β), increase the cost of producing non-CBD C, and decrease λ_i by legally capping the number of growers who can produce non-CBD crops. Intertemporal spacing would likely be effective as well, as it would reduce transmission rates. Recall that transmission rate by far had the strongest effect on tipping. Targeting this through intertemporal spacing of various hemp crops could dramatically reduce the social externality cost without passing any large cost onto growers. It may also be more politically feasible than some of the other options presented due to its low cost and relative light-handedness.

We offer three closing observations. First, the relevance of the work herein is without question. The proportion of hemp acres dedicated to CBD production was likely over 90% in 2019—and some argued higher still. For instance, *Hemp Industry Daily* estimates as much as 98% of acres in multiple regions to be planted for CBD (Drotleff, 2019). This proportion was anticipated to be, by some estimates, near 70% in 2020 (Sumner, 2020). While the chief cause of this decline is not immediately clear, at least two implications are: the vast majority of acres are still devoted to CBD, but there is an increase in acres of non-CBD production. This could be an indication of regional instances of tipping—the outcome suggested in this paper—or it simply could be a direct result of lower expected prices for CBD biomass after the glut experienced in 2019. In any case, the risk of cross-pollination has not decreased with this shift (it likely has grown). The second closing observation is that the ability to quantify policy impacts is currently limited because of present issues with data availability. Moreover, to do this is beyond the scope of the work herein, but is nonetheless a necessary undertaking and an inviting opportunity for future research. Finally, network effects of cross-pollination are not simply an academic problem. Cross-pollination caused major lawsuits over intellectual property in the early 2000s when Monsanto's Roundup-ready gene corn crops cross-pollinated neighboring fields that were growing corn from traditional seed. More recently, the marijuana industry has grappled with this same issue in the states that have legalized its production (Borque, 2019). Specifically, cross-pollination from other hemp crops degrades THC levels in marijuana. Our empirical specification of Jackson and Yariv's model could be applied to these types of agricultural applications as well.

NOTE

The form of Equation (6) is associated with uniform distribution of R occurring from 0 to R_{max}. For a more general form and detailed discussion of diffusion process modeling see Jackson and Yariv (2006).

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