Legalization of Cannabis in the USA:
A System Dynamics Approach to Drug Policy

Abstract

Colorado and Washington State have made history by approving measures to make marijuana sale and use legal for people over the age of 21, in direct opposition to federal law. While there is a sizable discussion of the actual repercussions that legal marijuana would entail, no one knows what will happen. Politicians in both states (and the federal government) must now make decisions on how best to implement these policies in a highly uncertain setting. Furthermore, the lack of specific information of existing black market trade makes pure economically driven policies highly speculative. The purpose of this paper is to aid in making such decisions by analyzing the relationship between the legal production of marijuana and the black market trade as well as their effects on the general population using System Dynamics. As there is big uncertainty about the process of starting and dependent cannabis use and the effect of legalization on these processes this subject needs further research. Looking at the market side of legalization preliminary conclusions can be drawn. These conclusions imply that regulating the supply side through permits is effective at fighting possible oversupply and heavy taxes might leave room for the illegal market to stay operational.

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1.   Introduction

The recent November 2012 election in the United States resulted in an unprecedented call for more lenient governmental policies that aim to end one of the longest lasting conflicts in American history. Not the war in Afghanistan or even the series of military actions in the Middle East, but the War on Drugs. Both Colorado and Washington State have made history by approving measures to make marijuana sale and use legal for people over the age of 21, in direct opposition to federal law (The Economist, 2012).

While there is a sizeable discussion of the actual repercussions that legal marijuana would entail, no one truly knows what will happen. There are ideas that point to large increases in state revenue in the form of tax benefits and legal savings (Ingold, 2012; Stiffler, 2012; Wyatt & Cooper, 2012) to even the far-reaching effects of limiting the power of Mexican drug cartels (Castillo & Wyatt, 2012).

Politicians in both states (and the federal government) must now make decisions on how best to implement these new policies (or to allow them) in a highly uncertain situation. Furthermore, the lack of specific information of existing black market trade makes any economically driven policies highly speculative.

Thus the purpose of this paper is to analyze the relationship between the legal production of marijuana and the black market trade as well as their effects on the general population using a System Dynamics (SD) approach. System Dynamics can help us by showing the dynamic behavior of the system. SD models can be used to test policies in a laboratory setting without fully implementing them in the real world. Throughout the course of this project, an exploratory SD model was created to test the effect of various policies relating to the legalization of marijuana in both Washington and Colorado State.

2.   Model Outline and Assumptions

2.1.   Colorado Amendment 64 and Washington I-502
The general intent of both measures is to safely regulate and tax marijuana use similar to that of alcohol. Each calls for a licensing system of production facilities, sets limits of personal use, determines a tax margin of retail marijuana, and even allocates where funds obtained from taxes will go. The two largest differences between the policies are in the tax rate: Colorado is calling for at least a 15% rate while Washington mandates 25%, and the restrictions on "personal grows": Colorado allows people to grow a maximum of 3 adult plants while Washington does not ("Colorado Amendment 64," 2012; "Washington Initiative 502," 2011).

Due to the large number of similarities between each law, the team perceived it valid to produce one model for use in both situations as the effect of personal grows on the overall market has shown to be negligible in a situation where home cultivation is already legal (the Netherlands) and thus omitted. Also neither law has explicitly stated the intended policy towards out-of-state customers, whether sale of cannabis to non-local customers will be allowed, out-of-state buyers will be required an extra provision, or only local residents will be permitted to buy cannabis products. Therefore the scope of this analysis does not include effects due to "drug tourism" from out-of-state consumers.

The crucial elements taken from each law, that have a direct impact on the general model structure, are therefore: delay times for obtaining permits, capacity allowances per permit, maximum number of permits per year, and tax rates.

2.2.   Conceptualization
To easily understand the model an aggregated causal loop diagram (Figure 1) has been made to show our view on the main functioning of the system. Parts of the causal loop diagram are based on earlier work by Pruyt (2009).

We start from the occasional users who can become addicted users depending on how much they smoke (average use per occasional user). People start smoking through peer pressure by both the occasional and addicted users (increasing the number of occasional users). Together these groups create a demand for cannabis.

An increased demand increases the price which causes more people to invest in cultivation facilities, which over time increases supply. This is valid for both the legal and the illegal market. The difference is that the illegal market has a risk which might diminish the investments in cultivation capacity.

Depending on the price of both legal and illegal cannabis and the risk of buying illegal cannabis people will choose between buying legal or illegal cannabis. The average price of

the used cannabis influences the average use of occasional users. This in its turn, together with the amount of occasional users, will influence the demand. We assume that people who are addicted use the same amount of cannabis and are not influenced by price change.

Together with the price, the use of illegal cannabis will provide criminality with money. If these amounts of money are too high, the social acceptance of using cannabis falls. Another factor influencing the social acceptance is the number of people with long term health problems due to cannabis. Addicted cannabis users have a high chance of developing long term mental problems and therefore diminish the social acceptance of cannabis use.
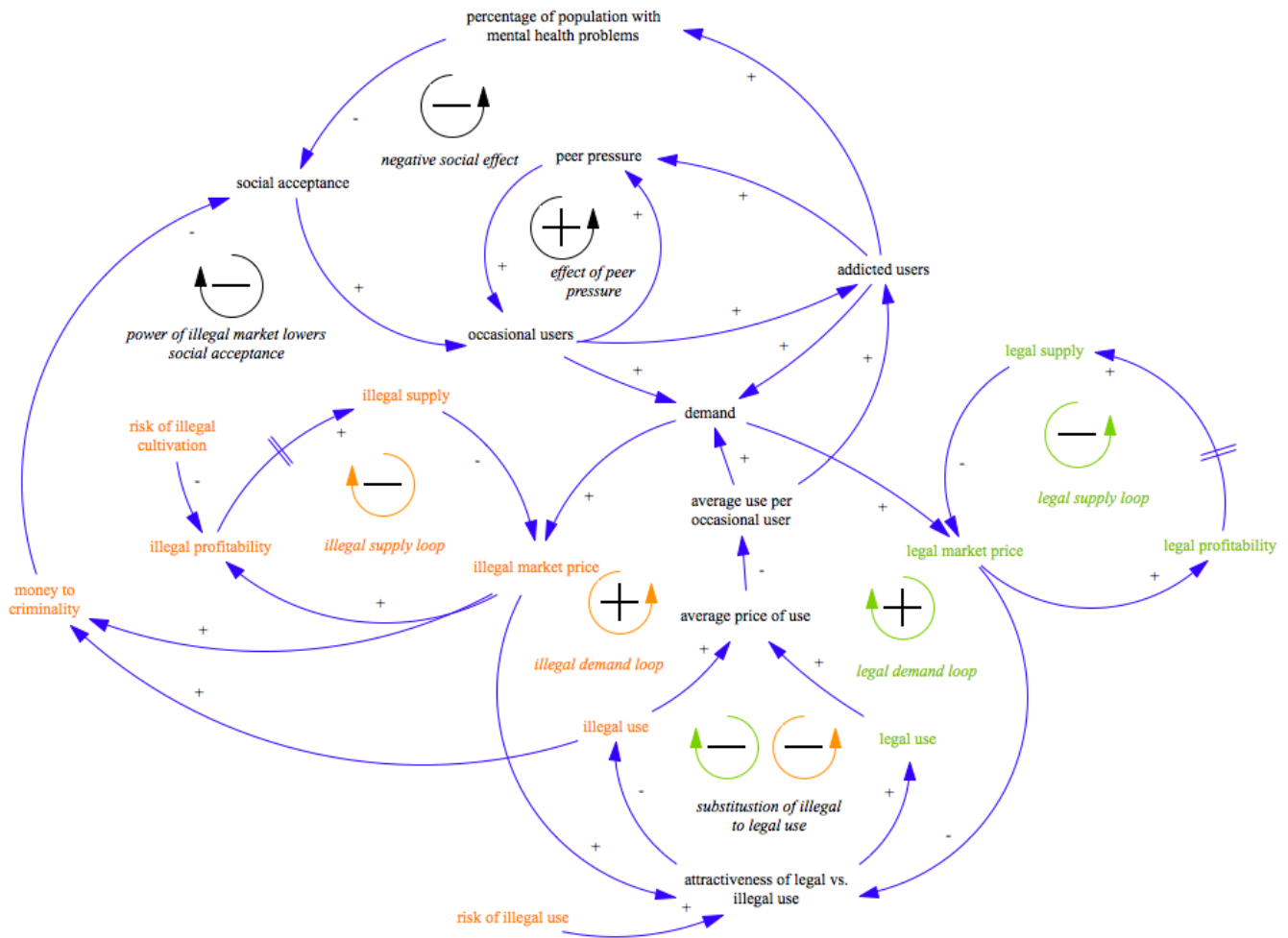

Figure 1: Aggregated Causal Loop Diagram

2.2.1. Population/Society
For the model the population is divided in terms of the usage of marijuana. There are three main sub-divisions in the population: *occasional cannabis users, addicted cannabis users,* and *ex cannabis users with risk of relapse* as well as one separate KPI (Key Performance Indicator) of *people with long term mental problems* (due to cannabis use).

Occasional users are increased by the flow *starting cannabis users* which is dependent on the social acceptance of cannabis and the total amount of people currently using cannabis multiplied by an "infection rate". The idea being that current users will encourage more

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people to use cannabis within their social sphere and if the social acceptance is also high, the number of people who start using cannabis will increase and thus become o*ccasional cannabis users*.

Occasional cannabis users become *addicted cannabis users* though the *addiction* flow, which is dependent on an *addiction curve*. The *addiction curve* is a lookup function dependent on the *average use of occasional cannabis user* and the assumption is that an occasional user has an exponentially increasing chance of becoming addicted if they use cannabis more frequently, ranging from a 0.1% chance if only using 1 gram per month to a 0.6% chance if using it daily (NIDA, 2011). The *addiction* rate multiplied by a *percentage of addicted people who develop mental problems (De Graaf et al., 2010)* also drives the amount of *people with long term mental problems,* a KPI for the population portion of this model. The percentage of the population with mental health problems due to cannabis lowers the general *social acceptance* and thus completes the main negative feedback loop in the population portion (as seen in Figure 1, aggregated causal loop diagram).

Addicted cannabis users become *ex cannabis users with risk of relapse* through *rehabilitation*, which is dependent on the *rehabilitation expenditures* and the *cost of rehabilitation* (Dennis et al., 2004; French et al., 2002). These newly rehabilitated users usually have the highest risk of *relapse,* thus becoming addicted users again, within the first 180 days (Moore & Budney, 2003). Also, according to Moore and Budney (2003) only 60% of rehabilitated users are in risk for relapse, meaning that 40% are effectively rehabilitated, thus the *ex-cannabis users with risk of relapse* stock is depleted by the *no relapse* flow, which constitutes 40% of users from the *rehabilitation* flow.

2.2.2. Legal Cultivation and Supply

Demand Loop
The main demand loop for legal trade is essentially driven by the occasional and addicted cannabis users, which create a total *demand for cannabis.* The *demand for cannabis* and the legal *cannabis supply* drive the *cannabis market price* through the *supply demand ratio* and the *effect of supply and demand on cannabis price.* The latter is a lookup function which assumes that when demand is five times greater than the supply (corresponding to a ratio of 0.2), the market price will increase by a factor of 4 and when supply is ten times greater than demand (thus a ratio of 10), the market price will be cut by 20% with a sharp exponential decrease between these two points. Refer to Table 2, lookups, for better description of supply/demand lookup.

Supply and Demand do not immediately affect the market price as there will be some delay between when cannabis is demanded, when the supply is available, and when their combined economic effects on market price actually occur. In other words, it will take time for cannabis producers to "see" the difference between supply and demand and thus take action (re-price their products) accordingly. The time period was assumed to be a three month delay as captured by the *supply demand ratio* variable in the full model Appendix A – Full Model and seen as a simple delay in the aggregated causal loop diagram Figure 1.

The legal *cannabis market price* therefore is equal to the *naked cost of legal cannabis*effect of supply demand on SD price*cannabis tax rate*. This market price, along with the *illegal cannabis market price* determine the *average price of used cannabis*, which is essentially describes the price which, on average, a user paid for cannabis. This average price is equal

to the faction of legal to total use times the legal market price, plus the fraction of illegal use to total use times the illegal market price as seen in Equation 1 below.

$$average\ price\ of\ used\ cannabis = \left(\frac{use}{use + illegal\ use} * cannabis\ market\ price\right)$$

$$+ \left(\frac{illegal\ use}{use + illegal\ use} * illegal\ cannabis\ market\ price\right)$$

EQ 1

This average price drives the *average use of occasional cannabis user* which, in turn, drives the total *demand for cannabis* and constitutes the main feedback loop in the legal trade section due to the Demand.

Supply Loop

The main supply loop for legal trade is, on one side, driven by the *cannabis market price*, and the other, by the *total demand* through its effect on the legal *use* of cannabis. The market price along with other factors such as: the production area allotted per permit, the yield per square meter and the naked cost of cannabis contribute to the *perceived annual profit growing legally*, which together with the demand and production capacity generates a *desired legal cultivation capacity.* This desired legal cultivation capacity is divided by the time it takes from the moment that one wants to start growing until the moment the cannabis will come onto the market to temper the amount of new capacity.

This desire generates a flow of *new cultivation capacity* which increases the amount of *Cultivation capacity under construction. Cultivation capacity* is realized after a fixed interval relating to the *average construction time*, the *average growing period*, and the *time it takes to get a permit.* Once *Cultivation capacity* has been realized it begins adding to the *cannabis supply* through *harvesting* or is decommissioned depending on the economic viability of cannabis production (dependent on perceived annual profit for growing legally). The legal *use* of cannabis decreases the legal *cannabis supply* and is expressed by the *demand for cannabis* *(1-*attractiveness of illegal use)*. This multiplication essentially scales the use between the legal and illegal markets depending on the society's willingness to purchase cannabis illegally.

The legal *cannabis supply*, of course contributes to the *supply demand ratio* and thus the *cannabis market price*, which constitutes the outer positive feedback loop due to Supply. The legal *use* of cannabis, however, also contributes to the *average price of used cannabis* as explained by Equation 1, which drives the total *demand for cannabis* and constitutes the inner feedback loop in the legal trade section due to the effect of legal market price on use.

In this model, cultivation capacity refers to physical space (in meters squared) allotted by permits to grow and harvest the cannabis plant. Once a cultivation area has been commissioned, meaning legally approved for a permit and built, it generates a constant flow of product relating to the amount of cannabis a single harvest in a given area can produce per month.

Cannabis plants take on average four to four and a half months to reach maturity (Yield-O-Rama, 2012), therefore, a given area of 1000m^2 can generate 400 kilograms (882 pounds) of

cannabis per harvest, which divided by the average growing period of 4.5 months, leads to a "constant" monthly output of 89 kilograms (196 pounds). It is assumed that growers will stagger plant growing periods to achieve a constant output per month. Also, once a cultivation area is granted a permit, it is assumed that it will continue to operate within legal standards and thus the government will not revoke permits once they are approved. This means that cultivation area (capacity) is only decreased due to economic factors (growers leaving the business due to low perceived annual profits).

2.2.3. Illegal Cultivation and Supply

Demand Loop
The illegal trade is similar to the legal but with additional factors to model the risk associated with black market trade. Risk in this model is assigned a numeric value corresponding to the related monetary penalty associated with a given crime, thus all risk factors are in terms of dollars or dollars per month.

Like the legal trade, the illegal trade is first driven by *demand for cannabis*. The *illegal cannabis supply demand ratio* the ratio of the *illegal cannabis supply* divided by the total *demand for cannabis*, which results in an *effect of supply demand on illegal cannabis price;* this effect is modeled as the same lookup function as explained in the legal section. The *illegal cannabis market price* therefore is equal to the *naked cost of illegal cannabis*effect of supply demand on illegal cannabis price*. This illegal market price is also used to determine the *average price of used cannabis* as explained in the previous section and constitutes the inner feedback loop due to the effect of illegal market price on use for the illegal trade section.

Supply Loop
The supply side is driven on one end by the *illegal cannabis market price* and the *total demand* as well as the *attractiveness of illegal use* through their cumulative effect on the *illegal use* of cannabis. The *attractiveness of illegal use* is dependent on the *ratio of cannabis market price vs perceived illegal cannabis market price* where it is assumed that when the legal price is ten times the perceived illegal price, taking into account the various risk factors for illegal purchase, the *attractiveness of illegal use* will be one and all users will purchase cannabis through the black market. This attractiveness level decreases linearly until both market prices are the same, in which case all users will prefer to purchase legally and the attractiveness will be zero.

The *illegal cannabis market price* and *perceived risk for illegal cultivation* will affect the *perceived annual profit growing illegally* which affects the *attractiveness of starting illegal cannabis cultivation.* The *attractiveness of starting illegal cannabis cultivation* directly generates an increase of *illegal cultivation capacity under construction* through the *illegal cultivation capacity* flow. Unlike the legal market, the illegal market does not need permits and can create supply much faster, only constrained by the growing period. Thus, *Illegal Cultivation capacity* is realized after a fixed interval relating to the average construction time and the average growing period only.

Once *illegal Cultivation capacity* has been realized it begins generating *illegal cannabis supply* through *illegal harvesting* and is decommissioned though *operational busts* by the police or by illegal growers. Illegal growers decommission cultivation capacity by taking into account the *perceived risk for illegal cultivation*. As noted in the beginning of this section, all risk factors are expressed in terms of their monetary value thus the *perceived risk for*

illegal cultivation directly affects decommissioning through the *effect of profitability and risk on decommissioning*

This effect is defined such that when the *perceived annual profit* equals the *perceived risk for illegal cultivation*(scaled to annual terms, in other words, multiplied by 12), the effect will be zero as no grower will decommission because the "risk is worth the money." As the scaled *perceived risk for illegal cultivation* becomes larger than the *perceived annual profit,* more illegal growers will decommission their operations to the point when perceived annual risk exceeds perceived annual profits by $50,000, 20% of the illegal cultivation capacity will be decommissioned per month.

The *illegal cannabis supply* is decreased through *supply busts* by the police or through *illegal use;* the latter is expressed by the *demand for cannabis *attractiveness of illegal use* and cannot exceed the *illegal cannabis supply.* This *illegal supply* changes the *illegal supply demand ratio,* which affects the *illegal market price* and constitutes the outer positive feedback loop due to the Supply side of illegal trade.

Table 1 and Table 2 show the used values for the above described variables and lookup functions.

Table 1: Constants and initial values used in the model

Life expectancy	960	months
Initial population	5,117,000	people
Infection rate	0.005	
Percentage of addicted people who develop mental problems	0.015	
Stopping rate	0.003	
Average use of Addicted User	28	grams/month/person
Average risk of relapse	0.6	
Cost of rehabilitation	1500	$/person
Average relapse time	2.5	months/person
init occasional cannabis users	400,000	people
init addicted cannabis users	50,000	people
init ex cannabis users with risk of relapse	100	people
Price elasticity of cannabis	-0.5	
Normal cannabis use	4	grams/month
init cannabis price	12	$/gram
naked cost of legal cannabis	10	$/gram
average harvest per m2	400	grams/m2/harvest
cost of setting up legal cultivation center	10,000	$/m2
init cultivation capacity under construction	0	m2
init cultivation capacity	0	m2
init cultivation capacity	0	gram
production area per permit	1,000	m2
time it takes to get a permit	4	months
average construction time of cultivation capacity	8	months
average growing period	4.5	months
chance of getting caught buying illegal	0.01	
effect of getting caught buying illegal	10	$/gram
naked cost of illegal cannabis	10	$/gram
average size of illegal cultivation capacity	30	m2
average illegal harvest per m2	400	gram/m2/harvest

```
init   illegal   cultivation   capacity   under        1,000  m2
construction
init illegal cultivation capacity                      34,000  m2
init illegal cannabis supply                        3,000,000  grams
chance of getting caught growing/supplying illegal       0.01
effect of getting caught growing illegal               10,000  $/m2
average construction time of illegal cultivation            1  month
capacity
Life expectancy                                           960  months
```

Table 2: Lookups used in Model

effect of illegal monthly revenues on social acceptance	([(-1e+07,0)-(5e+06,1)],(-1e+07,1),(0,1),(340000,0.5),(1e+06,0.35),(2e+06,0.25),(3.5e+06,0.21),(5e+06,0.2))
effect of percentage of population with mental problems on social acceptance	([(0,0)-(0.01,1)],(0,1),(0.0025,0.5),(0.005,0.25),(0.0075,0.12),(0.01,0))
addiction curve	([(1,0)-(28,0.008)],(1,0.001),(10,0.0012),(15,0.0015),(20,0.002),(24,0.0035),(28,0.006))
effect of supply demand on SD price	([(0,0)-(10,10)],(0,10),(0.2,4),(0.5,2),(1,1),(1.5,0.75),(2,0.5),(3,0.3),(10,0.2))
perceived annual profit growing legally	([(-1e+06,0)-(1e+07,0.08)],(-1e+06,0.08),(-800000,0.04),(-500000,0.02),(-300000,0.012),(-135000,0.005),(0,0),(1e+07,0))
effect of profitability on decommissioning	([(-1e+006,0)-(0,0.08)],(-1e+006,0.04),(-800000,0.02),(-500000,0.01),(-300000,0.006),(-135000,0.0025),(0,0))
attractiveness of illegal use	([(0,0)-(15,2)],(0,0),(1,0),(5,0.65),(10,1),(15,1))
effect of supply demand on illegal cannabis price	([(0,0)-(10,10)],(0,10),(0.2,4),(0.5,2),(1,1),(1.5,0.75),(2,0.5),(3,0.3),(10,0.2))
effect of profitability and risk on decommissioning	([(-100000,0)-(0,0.4)],(-100000,0.1),(-50000,0.05),(-30000,0.02),(-20000,0.01),(-10000,0.0025),(-5000,0.0012),(0,0))

3.   Validation and Testing

The purpose of validation is to check whether the model produces believable results and can be used for its intended purpose. The first part of the validation procedure consists of checking the model structure. Next, outcomes from the model are compared with expectations and/or real world figures. In the case of legal marijuana, hard data is not widely available as marijuana use and cultivation have been not been fully legalized throughout the world. Therefore the model must be evaluated by interpreting results and explaining if and why these results make sense.

3.1.   Model behavior

The base case scenario serves as the general template for describing model behavior and was made to assume that the government did not restrict the number of licenses, each license would allow for 1000 m² of cultivation area, along with a tax rate of 30%. The general trends seen throughout the model are described as follows:

3.1.1. Users
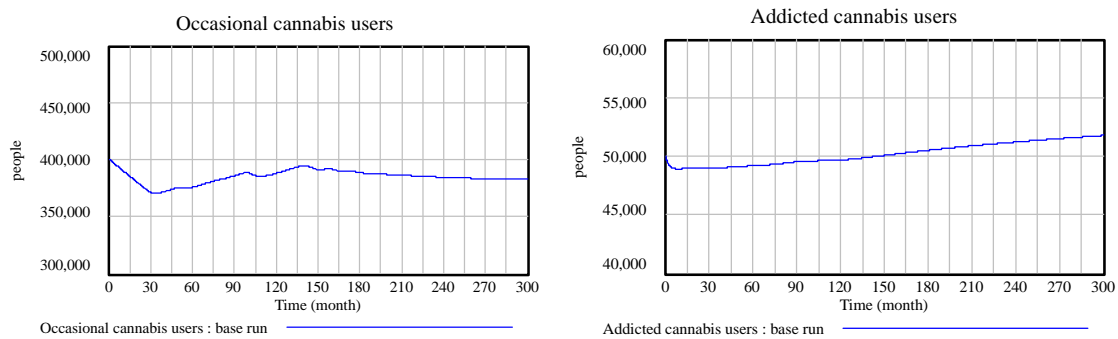
Figure 2: Occasional and addicted users

The occasional users graph shows an overall horizontal trend that never reaches above 400,000 people with a small characteristic decrease in the beginning months. This decrease is due to the illegal market still obtaining revenue initially, which negatively affects the social acceptance and, in turn, the occasional users as well. The addicted users also experience an initial decrease but not as pronounced because they are increased relative to the occasional users population and are thus less affected by social acceptance of cannabis. The addicted users also exhibit a slow upward trend that shows slight goal-seeking behavior later in time and is due to the slight decrease and eventual leveling of occasional users after month 150.

3.1.2. Cannabis Demand

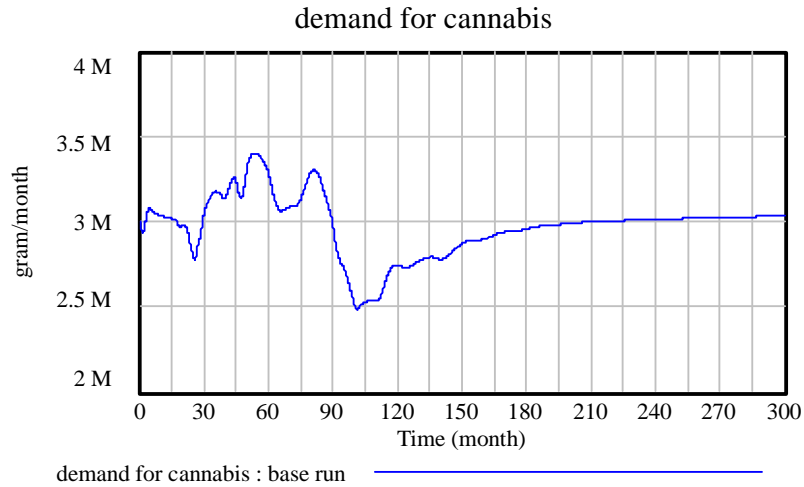

demand for cannabis

Figure 3: Demand for cannabis

It is assumed that consumer demand will essentially drive the market. What is seen in Figure 3 is an erratic initial behavior as cultivation capacity develops supply to meet demand and the legal cannabis market tends towards equilibrium. This equilibrium is depicted in the goal-seeking behavior from month 210 onwards. The market stabilization happens after month 90 and is mostly easily shown in the cultivation capacity graph in Figure 4 below.

3.1.3. Legal and Illegal Cultivation Capacity

Selected Variables
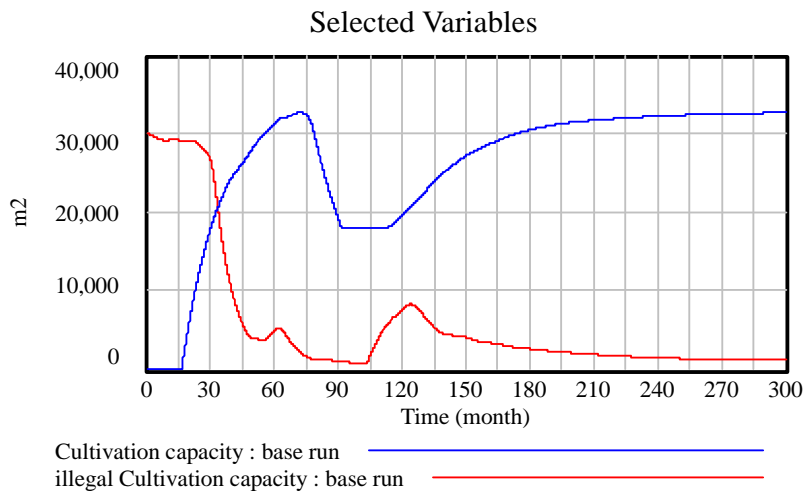
Figure 4: Illegal and legal cultivation capacity

Figure 4 above shows the interplay between the legal and illegal cultivation capacity. Initially there would be no legal cultivation capacity and the illegal side would support the entire market. After a delay corresponding to the time needed for permit approval, planting, growing, and first harvest, the legal side grows rapidly in contrast to the illegal market due to the perceived annual profits. This legal capacity overshoots in month 75, which leads to a rapid decline in capacity due to negative perceived annual profits, as seen in Figure 5 below.

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After the decline the legal capacity levels off which causes a slight increase in the illegal capacity as demand (Figure 3) increases from month 115. After month 90 perceived profits increase until month 120, the local maximum, which causes legal cultivation capacity to resume an upward trend and the illegal capacity to decline. Eventually all three graphs (legal/illegal capacity and legal profits) exhibit goal-seeking behavior towards the end.
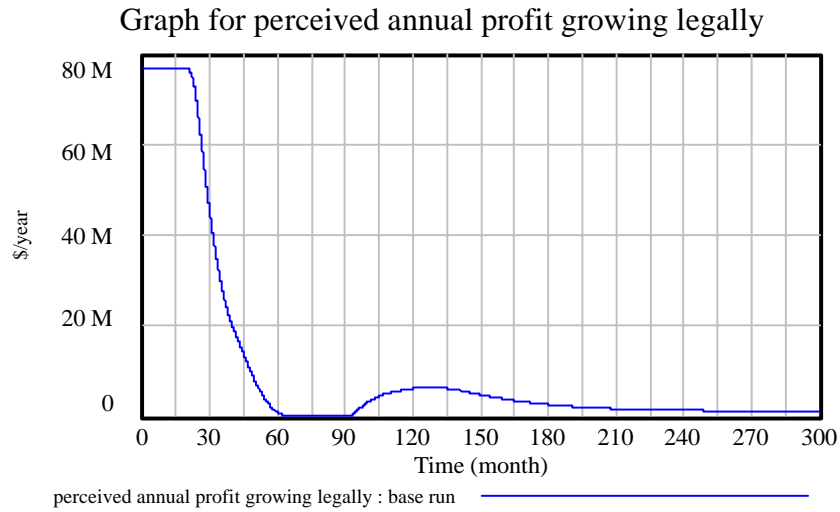
Graph for perceived annual profit growing legally

perceived annual profit growing legally : base run

Figure 5: Perceived annual profit growing legally

3.1.4. Legal and Illegal Market Price

Selected Variables

cannabis market price : base run
illegal cannabis market price : base run
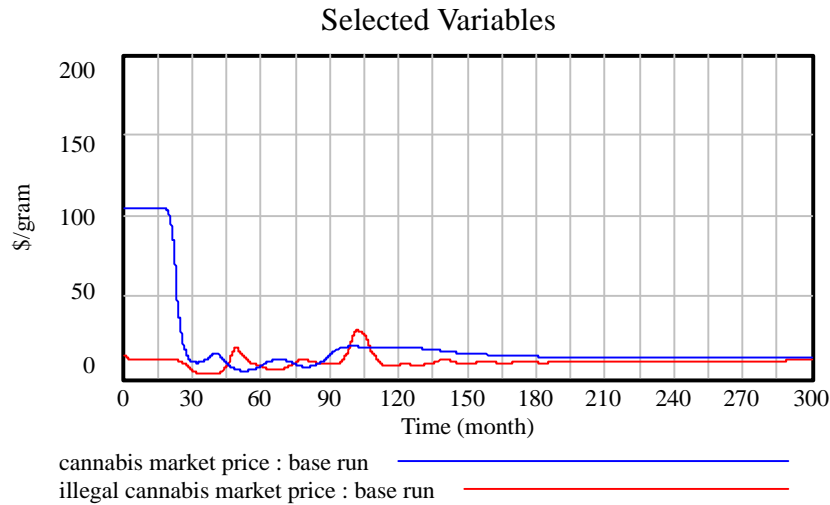
Figure 6: Illegal and legal cannabis market prices

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As can be expected, initially the legal market price is very high due to the constricted supply, which quickly drops off as cultivation capacity increases, and after which fluctuates and eventually tends towards an equilibrium price. The two small spikes seen in the illegal market price are due to discrepancies between legal and illegal capacity. Later the illegal market price fluctuates and settles on an equilibrium value slightly lower than the legal one.
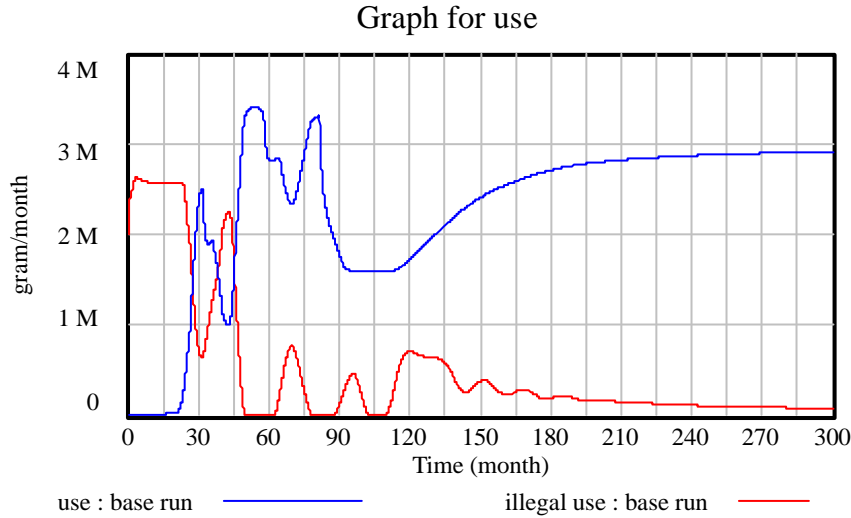
3.1.5. Cannabis Use

Figure 7: Legal and illegal use

The legal use, as seen in Figure 7, is initially zero due to lack of supply and the illegal use constitutes the full usage, which quickly declines as the legal capacity increases. Around month 30 the usage profiles intersect which corresponds to an intersection of the legal and illegal cultivation capacity as well (Figure 4). After initial erratic behavior, the legal use levels off at month 90 and increases with a goal-seeking trend. Illegal use, in comparison, fluctuates until month 120 where it attenuates down toward an equilibrium value; this is clearly seen in the envelope of the curve.

3.1.6. Monetary Revenues

Graph for Monthly Monetary Revenues

monthly revenues from illegal cannabis : base run
monthly revenues from legal cannabis : base run
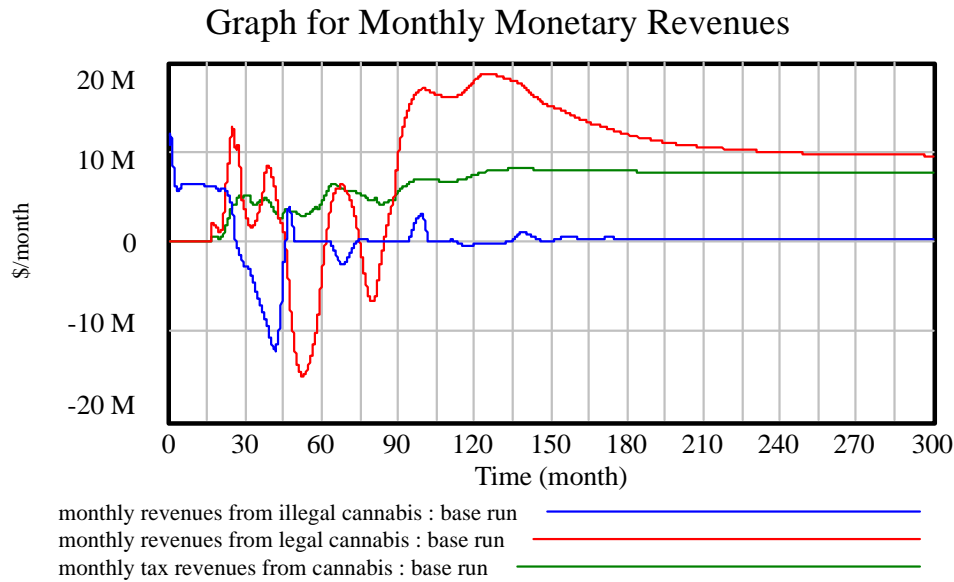monthly tax revenues from cannabis : base run

Figure 8: Monetary revenues

As can be expected from all previous trends, initially the monthly revenues to illegal sources are high in comparison to tax and legal revenues, but quickly drop and fluctuate around an equilibrium level close to zero. All three exhibit initial erratic behavior as the market forces balance with clear goal-seeking trends towards the end.

3.2.   Sensitivity

Sensitivity analysis is used to indicate which variables or assumptions contribute the largest additive effect to the overall output by performing numerous simulations across a range of variable input. If altering a particular variable drastically changes the model behavior, then this variable (and/or assumption) can be an opportunity for policy to alter the system towards more favorable outcomes. Sensitivity analysis also uncovers fundamental system components, which are important to understand in order to quantify the robustness of the model and the policies which are enacted to affect it. Also, highly sensitive variables can indicate key areas where added or increased research could greatly benefit policy makers interested in understanding the underlying system properties.

This analysis was performed using the Monte Carlo method, by varying each model variable randomly over a uniform distribution for a total number of 200 simulations. The results of each test are summarized below in their respective sections by employing sensitivity graphs. These graphs show the boundaries of a sensitivity test and are interpreted according to color. In each graph, 100% of all simulation outputs are within the Grey bounds, 95% are within the Blue, 75% within the Green, and 50% within the Yellow. Sensitivity graphs are displayed only for the model variables most relevant for each test. For a full description of the variables and values used for each test refer to Table 3.

For all Tests	Noise seed=1234 for 200 simulations
Initial Users and Initial illegal capacity and supply	
Init occasional cannabis users	RANDOM_UNIFORM (333000, 480000)
Init ex cannabis users with risk of relapse	RANDOM_UNIFORM (80, 120)
Init addicted cannabis users	RANDOM_UNIFORM (40000, 60000)
Init illegal cannabis supply	RANDOM_UNIFORM (1.67e6, 2.4e6)
Init illegal cultivation capacity	RANDOM_UNIFORM (25000, 36000)
Infection Rate/Stopping Rate	
Stopping rate	RANDOM_UNIFORM (0.001, 0.007)
Infection rate	RANDOM_UNIFORM (0.001, 0.1)
Percentage of addicted people who develop mental problems	RANDOM_UNIFORM (0.01, 0.02)
Initial Prices and Naked Cost	
Naked cost of illegal cannabis	RANDOM_UNIFORM (4, 12)
Naked cost of legal cannabis	RANDOM_UNIFORM (4, 12)
Init cannabis price	RANDOM_UNIFORM (8, 16)
Harvest Variables	
Average harvest per m2	RANDOM_UNIFORM (300, 500)
Average illegal harvest per m2	RANDOM_UNIFORM (300, 500)
Average growing period	RANDOM_UNIFORM (3,6)
Build Time	
Time it takes to get a permit	RANDOM_UNIFORM (0.25, 12)
Average construction time of cultivation capacity	RANDOM_UNIFORM (2, 14)
Average construction time of illegal cultivation capacity	RANDOM_UNIFORM (0.25, 2)
Price Elasticity	RANDOM_UNIFORM (300, 500)
Price elasticity of cannabis	RANDOM_UNIFORM (-0.3, 1)
Initial Values of Legal Side	
Init cannabis supply	RANDOM_UNIFORM (0, 100000)
Init cultivation capacity	RANDOM_UNIFORM (0, 100000)
Init cultivation capacity under construction	RANDOM_UNIFORM (0, 100000)

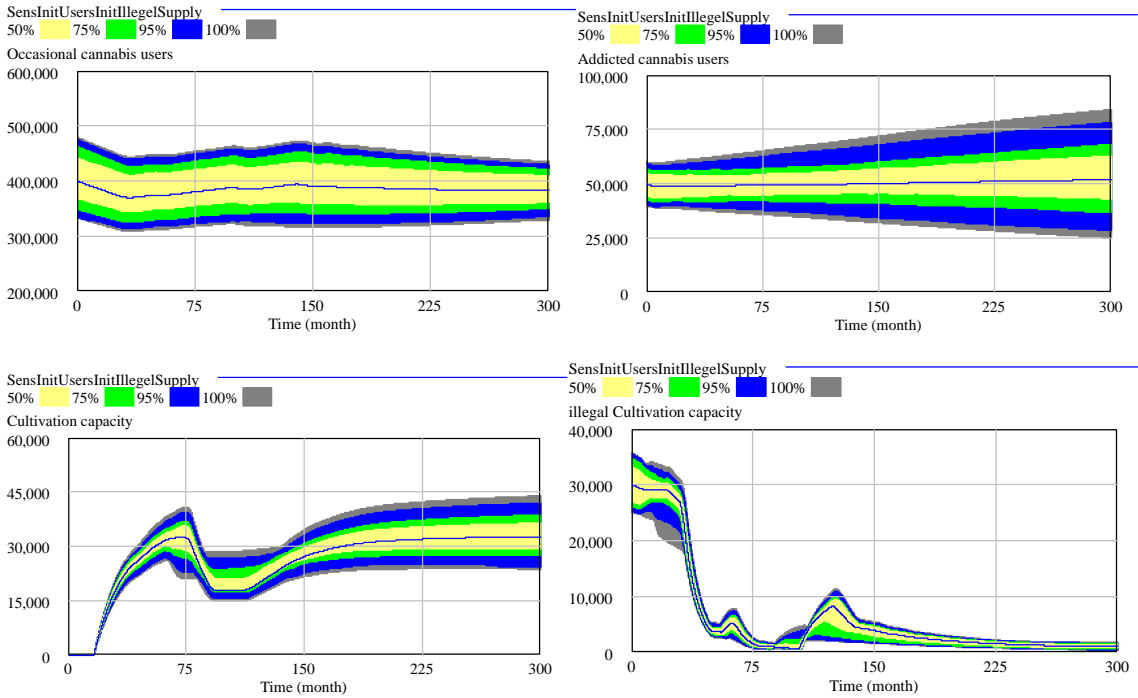## 3.2.1. Initial Users and Initial Illegal Capacity and Supply

Figure 9: Sensitivity of initial users and supply on occasional and addicted users and legal and illegal cultivation capacity

As can been seen from Figure 9, the general effects of changing the variables outlined in the corresponding section of Table 3 do relatively little to effect the overall behavior of the occasional cannabis users, the addicted users, the legal cultivation capacity and the legal cultivation capacity. The occasional users graph displays the general trend as nearly constant while the addicted users either increase or decrease linearly. Both supply trends follow the same behavior and are only marginally affected by the tested variables.

3.2.2. Infection rate/stopping rate
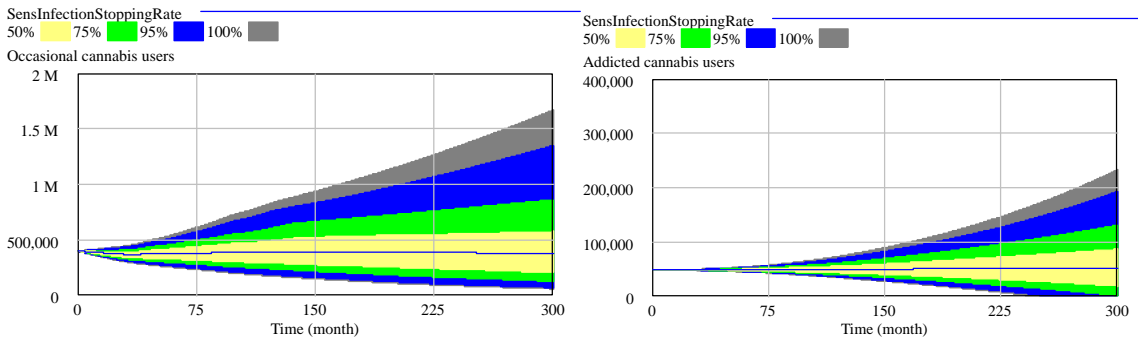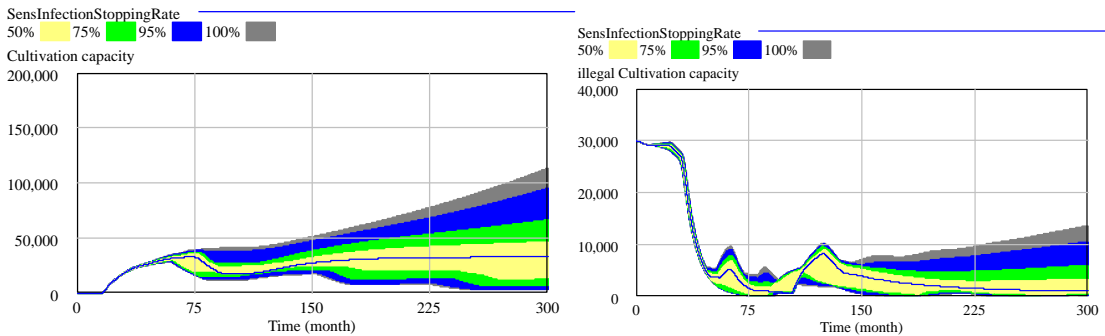
Figure 10: Sensitivity of infection and stopping rate on occasional and addicted users and legal and illegal cultivation capacity

The sensitivity graphs shown in Figure 10 above, however, indicate a very large model dependency on the rate at which people stop or begin using cannabis. All graphs follow their respective trends towards the beginning of each simulation period but drastically deviate over time. Occasional and addicted users exhibit large, even trend-altering deviations from their general behavior previously explained in the Model Behavior section of this report. The fact that even legal and illegal cultivation capacity is affected suggests that the model is highly user-driven, which would reflect the economic concept of consumer-generated demand.
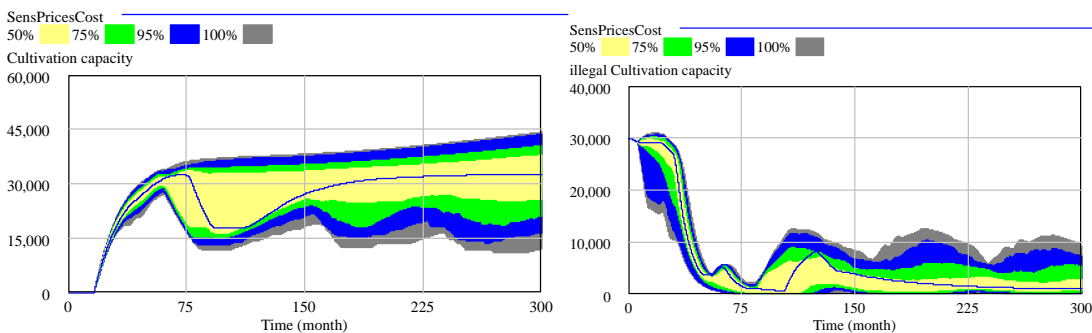
3.2.3. Initial Price and Naked Costs

Figure 11: Sensitivity of initial price and naked costs on legal and illegal cultivation capacity

The right-hand side of Figure 11 shows potentially trend-altering affects of initial prices on cultivation capacity. As seen in the upper Blue, Grey, and Green bars, certain simulations actually exhibit a trend where there is no large initial overshoot in legal supply; however the overall effect is contained within a relatively small bound. Therefore it appears that initial prices and cost of cannabis does have a small, but significant effect on the legal cultivation capacity. The small variation margins of the left-hand side with a clear general behavior indicates a smaller overall effect on illegal cultivation capacity.
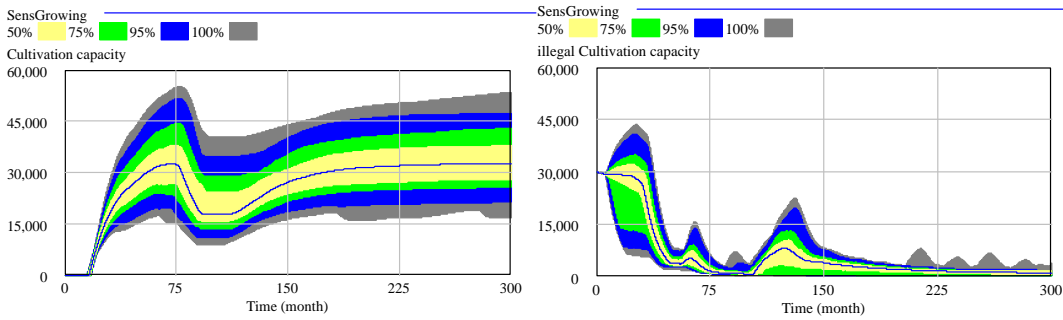
3.2.4. Harvest Variables

Figure 12: Sensitivity of harvest variables on legal and illegal cultivation capacity

While there is some variance seen in Figure 12 in both legal and illegal cultivation capacity, the general trend for both is maintained, thus the effect of changes in harvest patterns would appear to be relatively insignificant to system-level behavior.
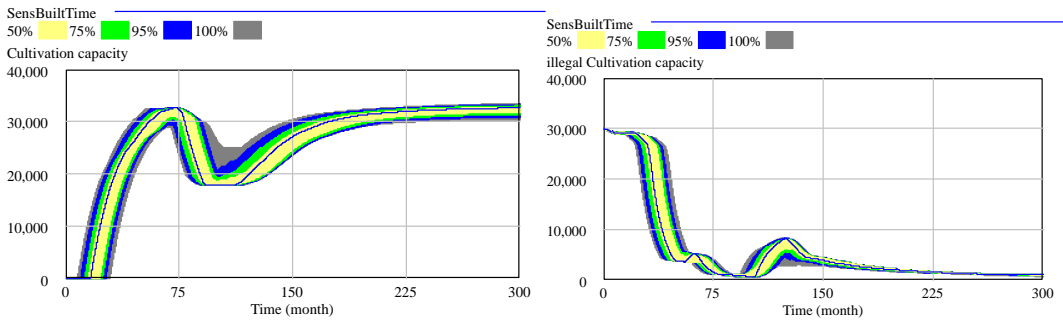
3.2.5. Build Time

Figure 13: Sensitivity of build time on legal and illegal cultivation capacity

The very small variation margin seen in Figure 13 above indicates that building times are relatively insignificant to the overall cultivation capacity in both legal and illegal realms.

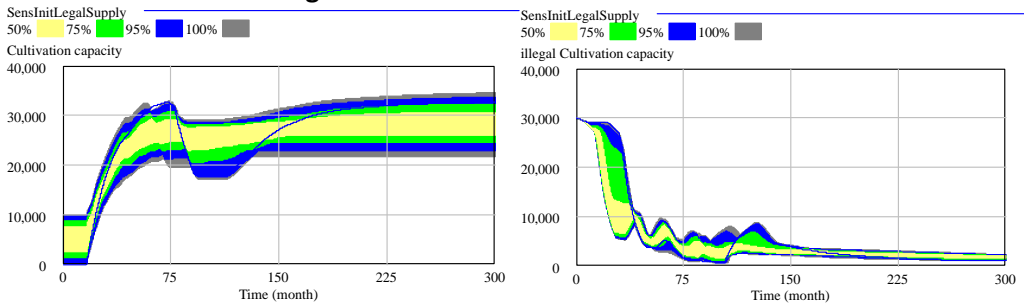### 3.2.6. Initial Values of Legal Side

Figure 14: Sensitivity of initial legal supply on legal and illegal cultivation capacity

Figure 14 displays a slight sensitivity in the legal cultivation side to initial values of the legal market but with a very small effect on the illegal cultivation capacity. Overall both cases follow their general trends throughout the test.

4. Policy Options

4.1. Limiting the number of permits

From the model behavior we see that there might be an overshoot in the legal cultivation capacity. This is caused by people not being sure about the size of the market and rushing into the new business. A possible way to temper the amount of people getting into the cultivation of cannabis is by limiting the number of permits granted.

A simple way of doing this is by giving out only a small amount of permits per year. Figure 15 shows that this does diminish overshoot and fluctuation in the cultivation capacity (PermitLimit1). The downside of this policy is that it takes longer before the cultivation capacity comes to its equilibrium (which is a little lower than the base run because of the lower social acceptance caused by the higher incomes for the illegal growers).

To counter this issue there is the possibility of making a stock of permits and adding a certain amount of permits to this stock every year. In that case the allocation of permits will be done via the principle of first come first serve. To make sure enough permits are available when the demand is highest (just after legalizing) the stock needs an initial supply, the change in the model is shown in Figure 16. Figure 15 shows the effect of this policy on the cultivation capacity (PermitLimit2). It shows that because if the directly available permits the initial growth is equal to the base run but after these initial permits run out people have to wait for new permits to start a cultivation center. This policy is effective at fighting the overshoot and rushing out after the overshoot.
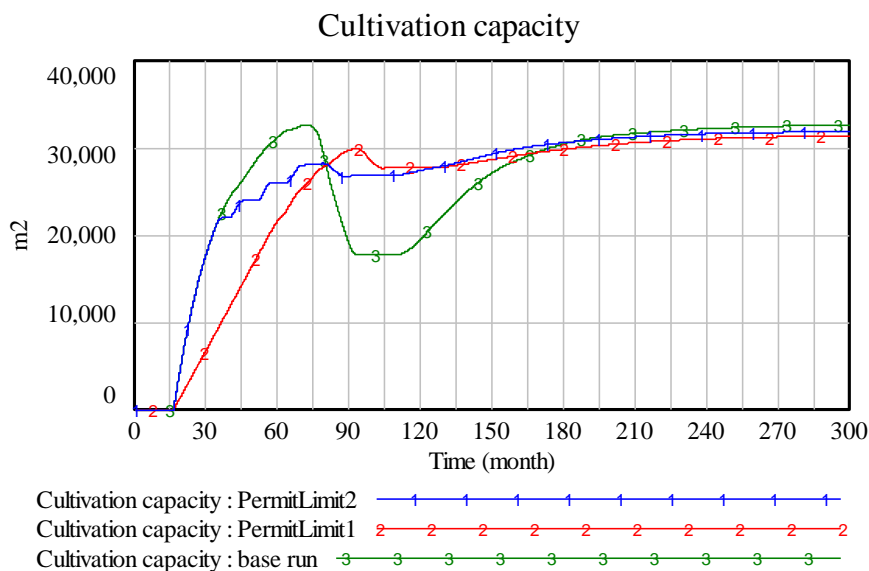

Figure 15: Limiting the number of permits

The initial available permits and the amount of extra permits available every year fixed numbers and have positive effect on the system under the used variables. Changes in variables like average harvest per square meter and average growing period would influence the amount of permits needed to meet the demand. If the demand is different than expected the number of permits also won't suffice. Preferably the initial and extra yearly available permits are dependent on system variables like yield per permit and demand, this still needs further study.
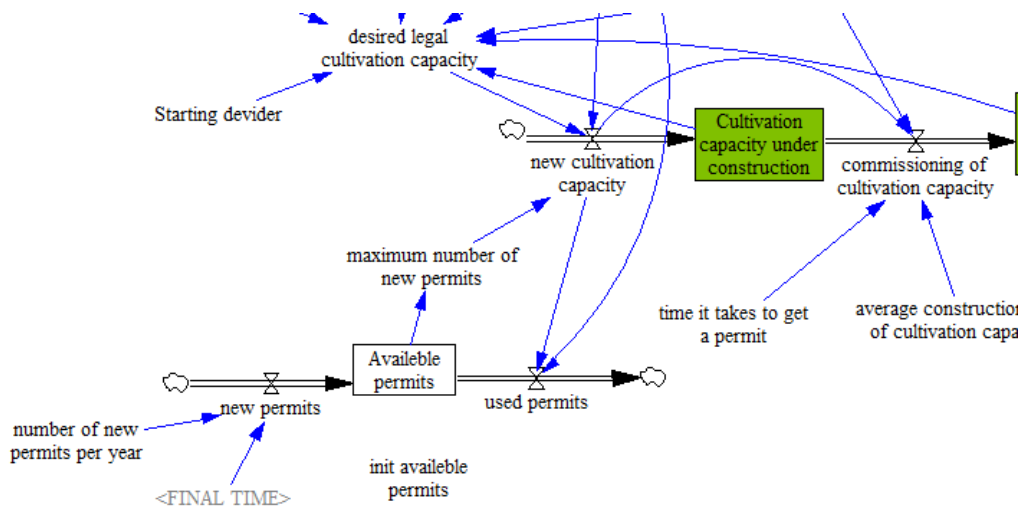
Figure 16: Model addition for available permits

4.2. Tax rates

An advantage of legalizing cannabis is the tax that can be drawn from the legal sales of cannabis. Both Amendment 64 and Initiative 502 state that the revenues will be used for the education and rehabilitation of cannabis users but having a tax that is too high might negatively influence the developing legal market. Higher tax rates mean higher prices and would likely result in more people choosing the untaxed illegal supply of cannabis. Low taxes mean lower prices, which will increase the average use of cannabis and thereby increase the number of addicted users.

The model response was tested against three different tax rates of 5%, 25% and 50%.

Figure 17 shows the effect of the different tax rates on the occasional and addicted users. Low tax rates cause low prices which cause more people getting addicted. Because more people will use cannabis there will be more peer pressure which causes even more occasional users and in time addicted users. Higher tax rates will cut average use and diminish both the occasional as the addicted users. It seems to be a good idea to have high taxes on cannabis.

The other effect of high taxes is that the price difference between legal and illegal cannabis grows. If the price difference is high enough people will be inclined to buy from the illegal market. Figure 18 shows the effect of the tax rates on the illegal cultivation capacity. Although in any case the illegal cultivation will drop dramatically, there will be more illegal cultivation at higher tax rates.

Figure 18 also shows the effect of high tax rates on illegal use, which causes oscillatitory behavior. This behavior is caused by the fact that people will opt for the illegal market when legal prices are high, however, the substitution from legal to illegal will lower demand for legal cannabis and will cause legal prices to drop. When legal prices drop, more people chose legal cannabis which drives the legal price up and again causes more people to substitute for the illegal market, continuing the cycle. In this proces more money is going to illegal cannabis growers as shown in Figure 19.

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Looking at these results it can be argued that high tax rates are not very effective in attenuating the illegal market.
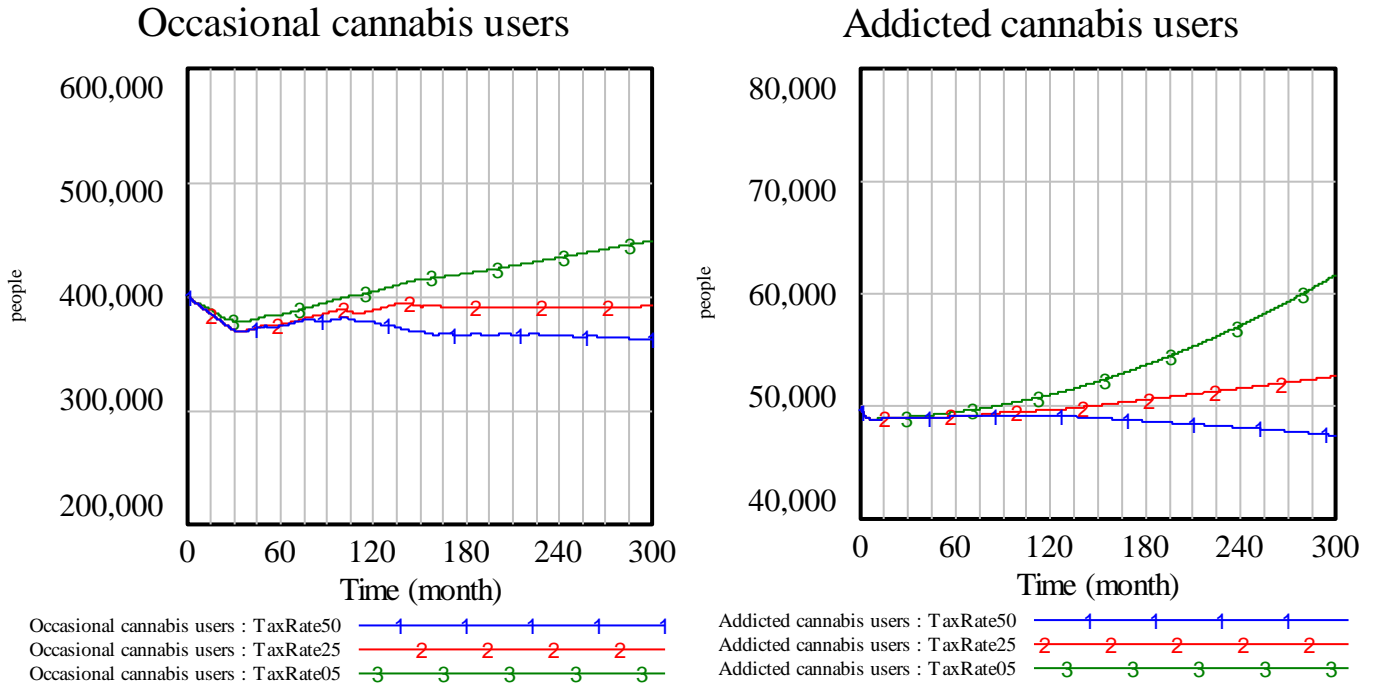

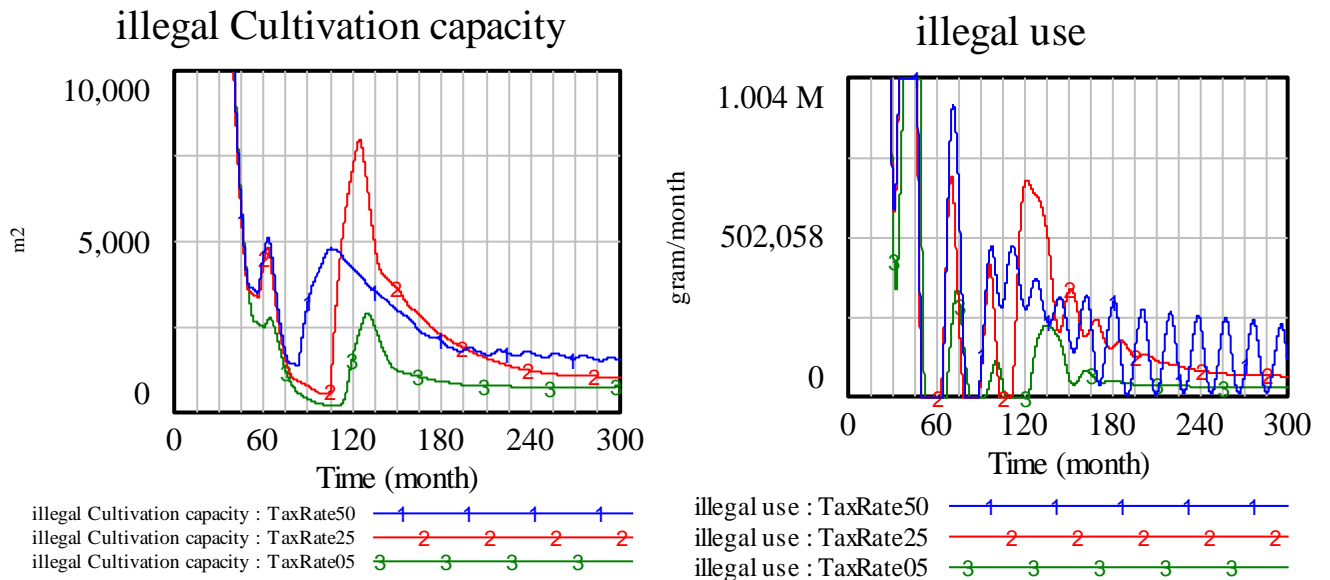Figure 17: Effects of tax rates on occasional and addicted users

Figure 18: Effect of tax rates on illegal cultivation capacity and use

Cummulative money to illegal cannabis growers (criminals)

"Cummulative money to illegal cannabis growers (criminals)" : TaxRate50 —1——1——1——1——1——1——1—
"Cummulative money to illegal cannabis growers (criminals)" : TaxRate25 —2——2——2——2——2——2——2—
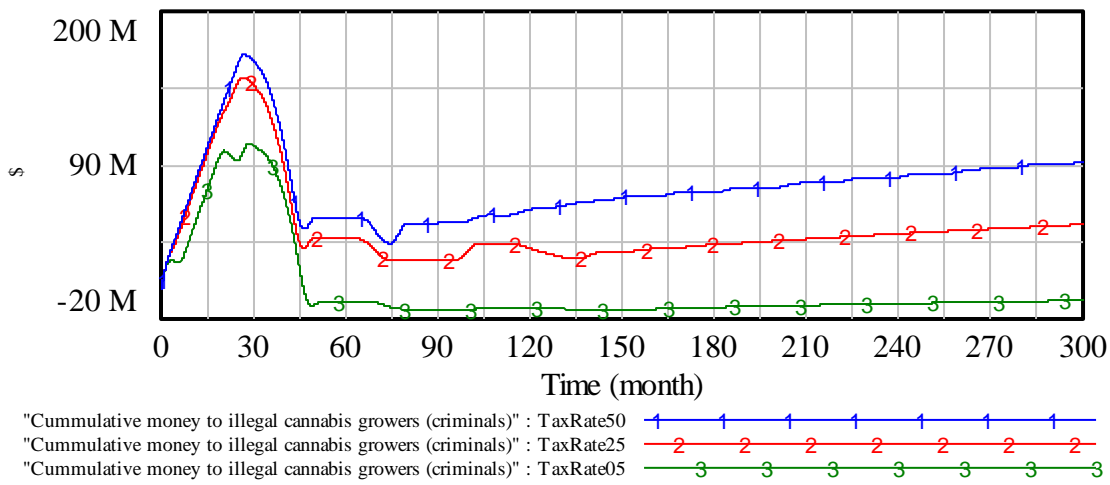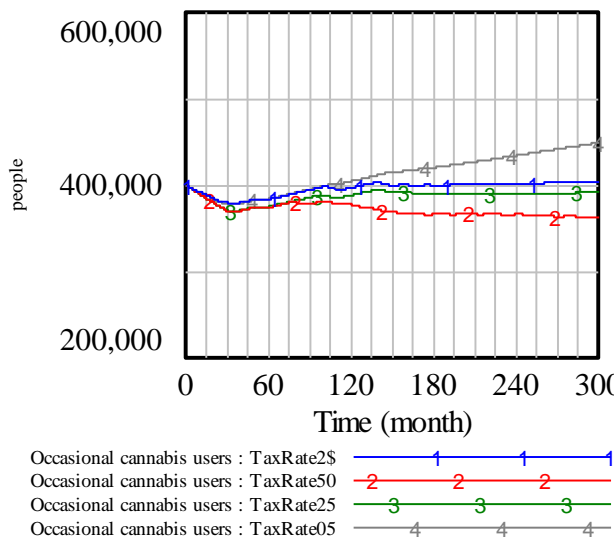"Cummulative money to illegal cannabis growers (criminals)" : TaxRate05 —3——3——3——3——3——3——3—

Figure 19: Effect of tax on cumulative money going to illegal growers

Another option of taxing cannabis sale is to set a fixed price on every sold unit, which is already the case for alcohol in most states. As a test case, a fixed tax was used of 2$/gram which is around 20% of the assumed naked cost of cannabis. The effects on the users are shown in Figure 20. The effect is not optimal as the number of addicted users still increases, but less in comparison to the case of only taxing 5%. The effect on the money going to the illegal market is shown in Figure 21; notice that the fixed price policy has the same general behavior as a tax rate of only 5%.

## Occasional cannabis users

Occasional cannabis users : TaxRate2$ —1——1——1—
Occasional cannabis users : TaxRate50 —2——2——2—
Occasional cannabis users : TaxRate25 —3——3——3—
Occasional cannabis users : TaxRate05 —4——4——4—

Addicted cannabis users

Addicted cannabis users : TaxRate2$ —1——1——1—
Addicted cannabis users : TaxRate50 —2——2——2—
Addicted cannabis users : TaxRate25 —3——3——3—
Addicted cannabis users : TaxRate05 —4——4——4—
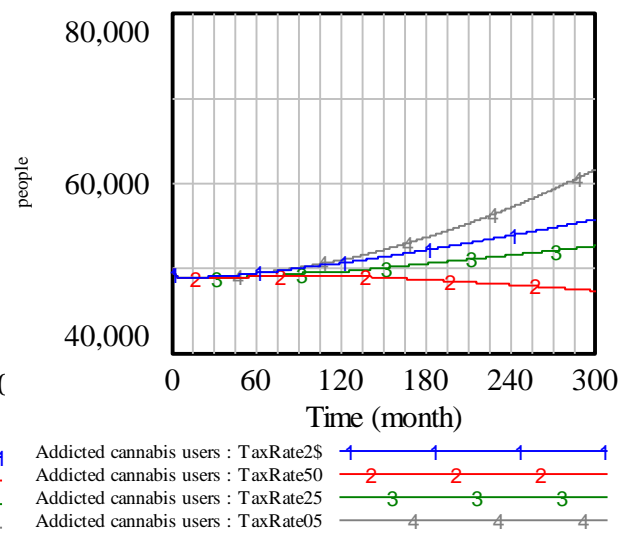
Figure 20: Effect of a fixed tax on users

Cummulative money to illegal cannabis growers (criminals)

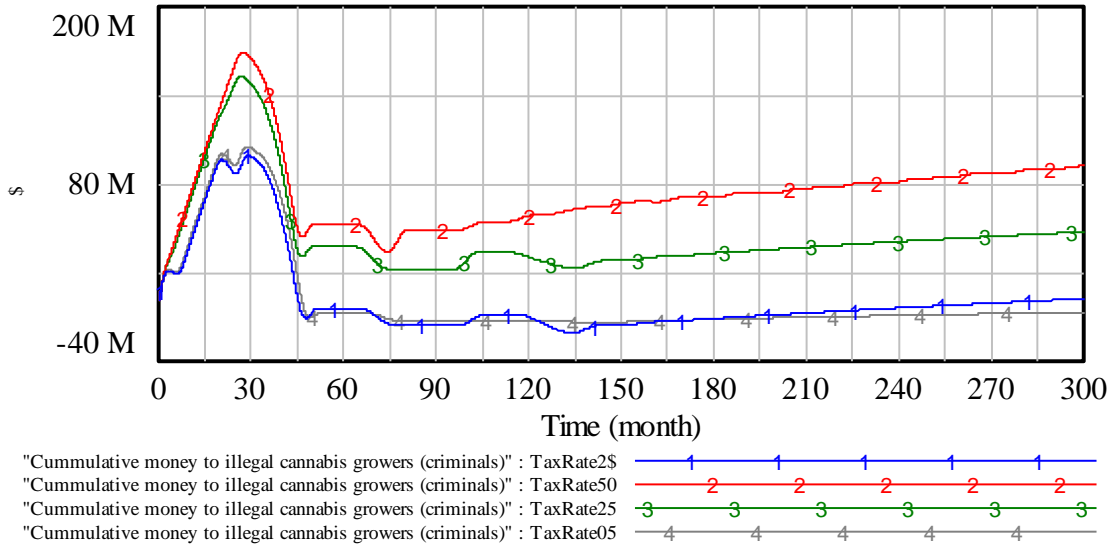|	
"Cummulative money to illegal cannabis growers (criminals)" : TaxRate2$	1
"Cummulative money to illegal cannabis growers (criminals)" : TaxRate50	2
"Cummulative money to illegal cannabis growers (criminals)" : TaxRate25	3
"Cummulative money to illegal cannabis growers (criminals)" : TaxRate05	4

Figure 21: Effect of fixed tax on money going to illegal growers

The effect of various taxing options on government income is shown in Figure 22. Here it also shows that, although taxing by 50% results in a larger income, that taxing a fixed amount of 2$/gram is a better option due to its effect of decreasing money to illegal sources as shown previously in Figure 21.
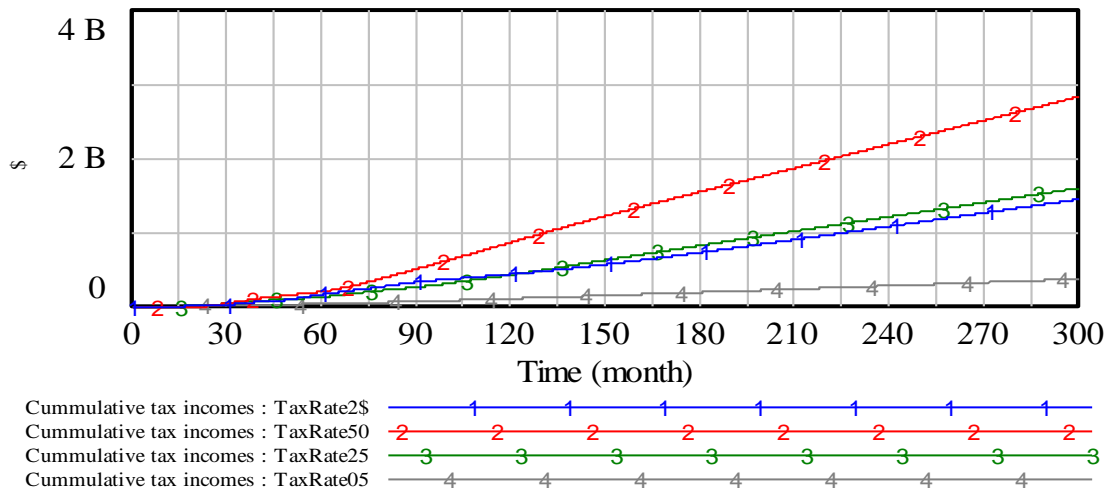
Cummulative tax incomes

Cummulative tax incomes : TaxRate2$	1
Cummulative tax incomes : TaxRate50	2
Cummulative tax incomes : TaxRate25	3
Cummulative tax incomes : TaxRate05	4

Figure 22: Effect of different taxes on government incomes

4.3. Higher risk of illegal cultivation

Increasing the risk of illegal business typically only serves to drive up the price of illegal cannabis which results in increased profits to criminals when there is no other way of obtaining the product legally. When cannabis is legalized, this changes.

People will be able to buy from legal sources, so increasing the price of illegal cannabis by making the risk of getting caught higher will make more people buy from legal sources. The difference is shown in Figure 23. Where the run 'CatchChanceHigh' (2) is the situation where there is a higher chance of getting caught right from the beginning. The result is a higher cannabis price and because there is no legal supply yet, higher profits for criminals. The run 'CatchChanceStep' (1) increases the chance of being caught only after 48 months have passed to allow for the legal market to establish itself. This policy effectively reduces the illegal market and limits its growth, even below the base run, towards the end of the simulation.
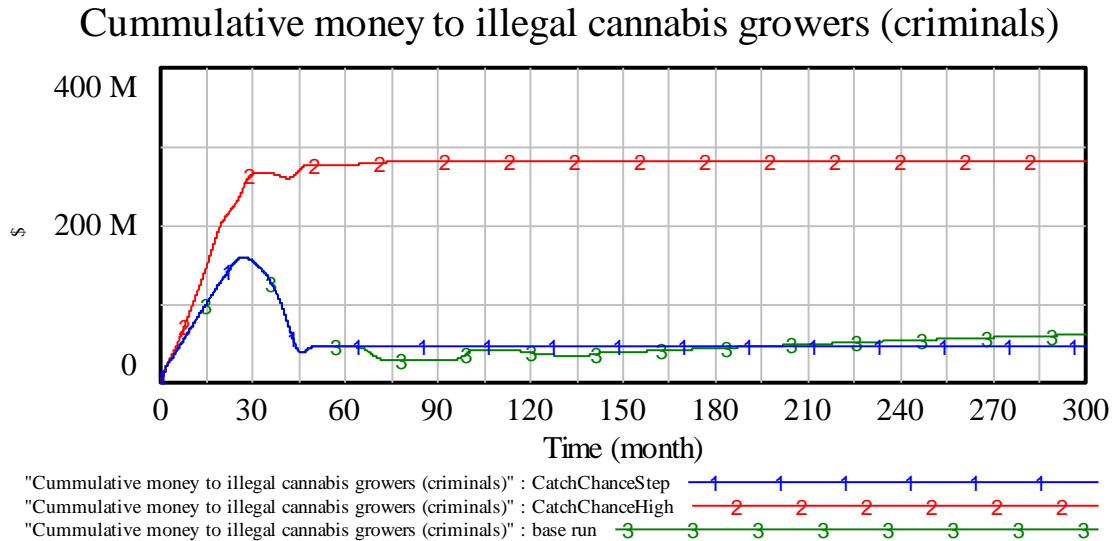

Figure 23: Effect of higher chances of getting caught on money going to criminality

4.4. Investing in education and rehabilitation

With the money made from taxes it is possible to educate people, presumably causing less people to start smoking and more people to give up their habit before they get addicted (Ennett, Tobler, Ringwalt, & Flewelling, 1994; Mdford, 2000; White & Pitts, 1998). The effectiveness of education in the research ranges from 0.4% to 15% (0.4% to 15% less cannabis use). There is a lack of data on the cost of this education. Therefore the model is tested with education influencing the social acceptance with the above mentioned effectiveness. The result on the occasional and addicted users is shown in Figure 24. It seems that education has a major effect on the users. Although more research has to be done in the cost of this education, it seems appropriate to invest in making people more aware of the issues related to drugs.
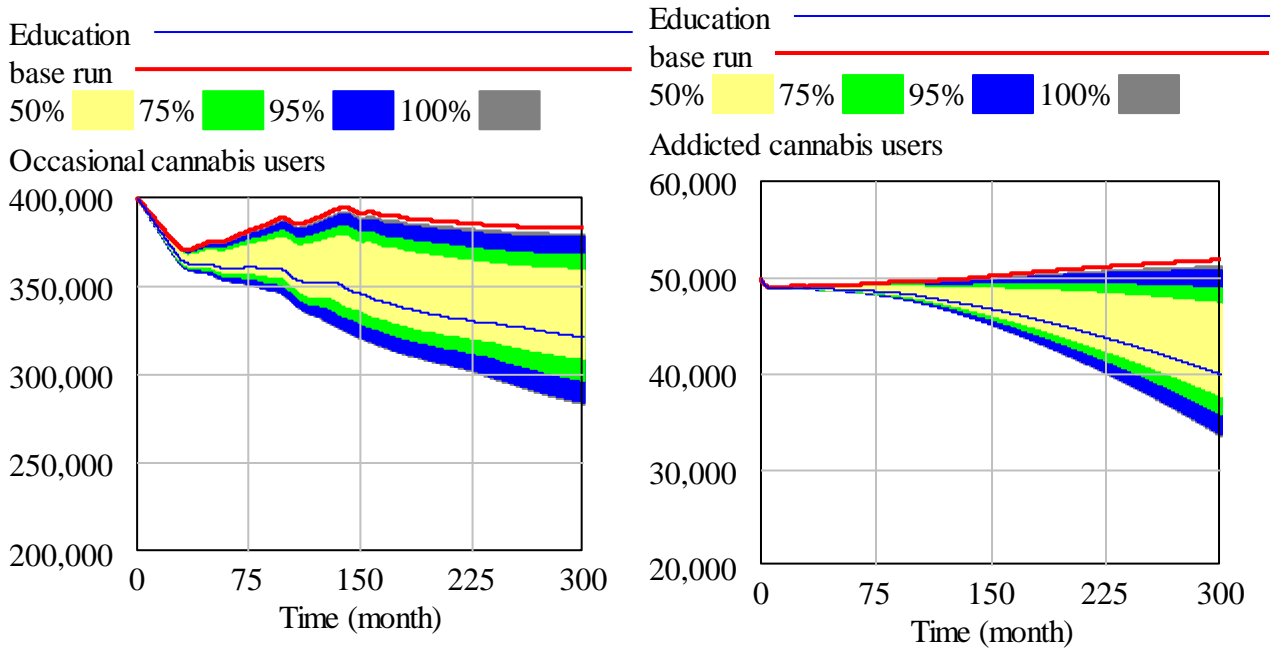
Figure 24: Effect of education on occasional and addicted users

Part of the tax revenues can also be spend on rehabilitation of addicted users. Figure 25 shows the effect of spending 30% of monthly tax revenues on treatment.
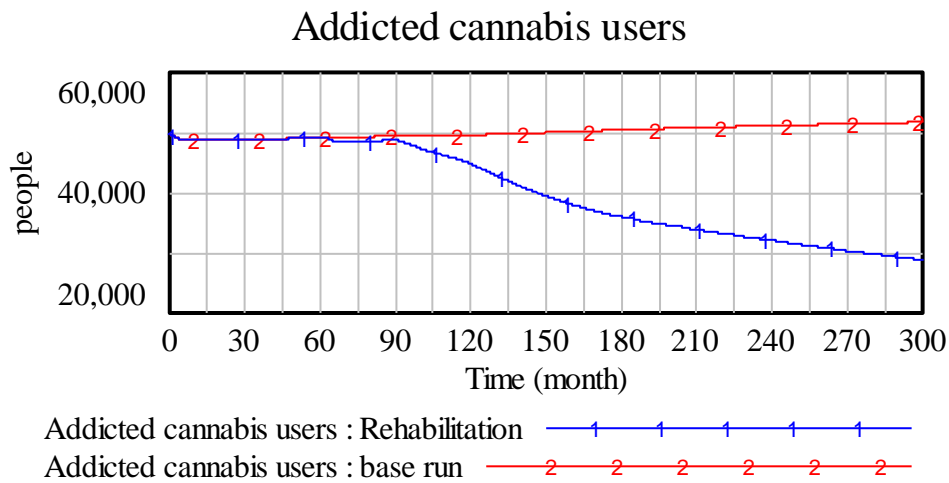

Figure 25: Investing 30% of tax revenue on rehabilitation

5.   Conclusions and Recommendations

In this paper a Systems Dynamics model was created to explain the effects of cannabis legalization in both Washington and Colorado State and to analyze the interplay between the legal and illegal cannabis markets. While the nature of illegal markets makes specific data difficult to obtain, they are known to follow basic economic assumptions, which allow for relevant and useful models. As stated by Pino Arlacchi in regards to illegal markets: "*The internal dynamics of illicit markets are often described by the popular press as being typically obscure and inspired by a mysterious logic ultimately eluding analysis. In fact, a number of studies have shown that we are faced with rational economic phenomena and well-structured 'industries'* (Ruggiero, South, & Taylor, 1998, p. 203).

The general purpose of the systems dynamics approach is to uncover the fundamental structure of and give some insight to the general behavior of a given system, not to make precise forecasts. In this context, SD modeling is useful in that it enables simulation of simplified reality to assist in decision making for policy. Thus it must be emphasized that conclusions drawn from such an approach are general and *descriptive* rather than *predictive*.

The first conclusion is related to the model structure itself as indicated through the Sensitivity Analysis section of this report. The rates at which people start and stop using cannabis are, by far, the most influential elements on the system outputs. In this model, the "infection rate" was conceptualized as the effect of social pressure or encouragement of non-users to try cannabis by current users. While concepts like social pressure are arguably abstract, such a high level of sensitivity suggests that further research, aimed at quantifying and explaining the rational for people to begin using cannabis, could present unique benefits towards creating effective drug policies.

The following conclusions are related to possible methods of implementation for legalizing cannabis as elaborated upon in the Policy Analysis of this report.

The permit study implies that cultivation capacity should be limited to prevent supply overshoots in the market. However, it is important to base the number of permits allowed annually or monthly on currently known cultivation capacity. While this may seem self-explanatory, Figure 15 demonstrates the necessity of having a sufficient number of permits available in the beginning, thus effectively not limiting capacity, when demand is high, but later limit capacity as the legal market supply increases.

In relation to optimal tax rates, we recommended policy makers to consider a fixed tax, on a per rata basis, as well as traditional percentage taxes. The fundamental necessity is that taxes are not so high as to discourage the public from legal use, yet high enough to curb demand and generate a useful amount of income for the government.

The brief risk study would suggest that a more prudent strategy could be to first allow the legal market to stabilize before taking aggressive (and potentially costly) action, intended to increase the risk of buying illegal cannabis, against illicit activities. It may be the case that legal market forces, under sufficient regulation, will effectively attenuate the illegal market to acceptable or negligible levels as explored in Figure 23.

The authors stress that effective cannabis policy should be made with legal regulation *and* illegal attenuation in mind. While a given policy may exhibit desirable qualities in one realm,

for example revenue generation, it is equally or even more important to consider the effects of any policy on the overall system and welfare of the citizens.

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Model