Bist, Kevin

From: Gary Knipe <Gary.Knipe@arishort.com>
Sent: Monday, January 12, 2015 2:48 PM
To: Nelson, Patricia A
Subject: Aris Horticulture Financial Information
Attachments: Charlotte's Web Expense Estimates.xlsx

Hello Patty,

Attached is a summary of our financial projections for CW production at our farm in Alva, FL. I have broken this down into capital cost for startup and annual reoccurring expenses. The numbers are based on 1925 plants per year @.79 lb. per = 1520 lbs.

These are our Phase I start up numbers. We have a significant Phase II planned to come online in 6 months to a year as the patient base expands.

I hope this helps you. Please let me know if you have any questions or need additional information.

Thanks

Gary Knipe
Managing Director
Aris Horticulture, Inc.
2201 Owanita Rd.
Alva, FL 33920
Office: 800-232-9557 ext.3317
Cell: 239-633-6867
Fax: 239-728-3172
Arishort.com

Aris

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CATEGORY	PHASE I EXPENSE ESTIMATES			
Capital	FACILITIES - CONSTRUCTION	$	834,000.00	
Capital	LAB EQUIPMENT - EXRACTION	$	200,000.00	
Capital	COMPUTER & SECURITY	$	206,700.00	
	SUB-TOTAL CAPITAL			**$ 1,240,700.00**
Annual	LICENSE	$	150,000.00	
Annual	BOND	$	150,000.00	
Annual	OPERATION EXPENSES	$	619,963.14	
Annual	MEDICAL DIRECTOR	$	60,000.00	
	SUB-TOTAL ANNUAL			**$ 979,963.14**
	GRAND TOTAL			**$ 2,220,663.14**

Bist, Kevin

From: Nelson, Patricia A
Sent: Monday, February 02, 2015 9:35 AM
To: Watson.strategies@comcast.net
Subject: Cost Estimates

Ron,

I saw the following quote in the news today. Any information the FMCA can share with us would be greatly appreciated.

Patty

"We've talked to people with large operations in Colorado, California and Canada," said Cerise Naylor executive director of the another business group, the Florida Medical Cannabis Association. "They're all saying you're going to be spending hundreds of thousands of dollars a month just on your lighting costs. And then you're going to have to keep your air conditioning on constantly ... because those lights produce so much heat."

Patricia Nelson
Director
Office of Compassionate Use
Florida Department of Health

Bist, Kevin

From: cnaylor@flmca.com
Sent: Tuesday, February 03, 2015 11:59 PM
To: Nelson, Patricia A
Subject: Production Cost Est.

Hi Patricia,

I've been working on a production cost estimate review tailored for Florida (patient demand/Florida grower capabilities) and I'm just working to finish up a few charts. I will try to have it to you by tomorrow morning.

Cerise Naylor
Executive Director
3262 Elizabeth Street, Suite 2
Miami, FL 33133
Office: (850)290-3865
Cell: (772)214-2900
www.FLMCA.com

Bist, Kevin

From: Nelson, Patricia A
Sent: Wednesday, February 04, 2015 5:35 AM
To: cnaylor@flmca.com
Subject: Re: Production Cost Est.

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Sent: Wednesday, February 04, 2015 7:55 AM
To: Rogers, Reneeka
Subject: FW: Aris Horticulture Financial Information
Attachments: Charlotte's Web Expense Estimates.xlsx

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Director
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Florida Department of Health

Bist, Kevin

From: cnaylor@flmca.com
Sent: Wednesday, February 04, 2015 4:52 PM
To: Nelson, Patricia A
Subject: RE: Production Cost Est.
Attachments: Florida Est. Med Cannabis Production Cost.pdf

OK, I really hope this is helpful!! As you know this is a real shot in the dark. Each operation is going to have drastically different start up and annual production costs. The last page could probably be dissected to find out a rough estimate of the costs of those items however that will take some more time and seemed to be brushed off by growers in other states when I asked about them. I'm not sure how or why because just looking at it gives me a panic attack! Many large nurseries in Florida have a lot of the equipment needed to grow cannabis already.
Call me if you have any questions on the numbers.

Cerise
772-214-2900

From: Nelson, Patricia A [mailto:Patricia.Nelson@flhealth.gov]
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To: cnaylor@flmca.com
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Medical Cannabis Production Cost:
Florida Estimate

Basic Florida Patient Statistics

Population: 19,317,568

Cancer Patient Population: 835,060[1]

Epilepsy Population: 394,945[2]

Parkinson's Population: 44,052[3]

Multiple Sclerosis Population: 21,375[4]

ALS Population: 1,931.76[5]

Likely Patient Usage

Cancer: 5,928.926 (.71%)[1a]

Epilepsy: 3,400 (.86%)[2a]

Parkinson's: 6,167.28 (14%)[3a]

MS: 2,992.5 (14%)[3a]

ALS: 270.45 (14%)[3a]

Total Patient Population:
1,297,363.76

Total Patient Likely Usage:
18,759.156

1. Florida Office of Economic & Demographic Research—Revenue Estimate Conference pg. 658 –660

1a. Among the states where medical cannabis is legal the lowest percentage found of cancer patients who use medical cannabis is .71%. In an effort to remaining conservative in our projections this is the figure used.

2. Epilepsy Foundation of America

2a. To estimate the total likely patients to use medical cannabis, the OED figure of 3,400 users was used for state-wide projections. This is based on an average of less than 1% of all epilepsy patients from eight other states use medical marijuana.

3. American Parkinson Disease Association www.apdaparkinson.org—See Florida Population 60+ Years Chart TABLE 1

3a. 14% was used for all three diseases listed in this report that cause muscle spasms. The total likely patients from those three render a total number that is 21% of the total medical cannabis use in the state. This figure (21%) was determined by taking the average of the states with the lowest percentage claiming to use cannabis to treat muscle spasms (Oregon 14.5%) to the highest (Colorado 27%).

4. National Multiple Sclerosis Society www.nationalmssociety.org

5. ALS Association www.alsa.org—8 out of 100,000 living in Florida with ALS (1,545.408) 2 out of 100,000 annual diagnosis (386.352); unknown mortality rate.

Medical Cannabis Production Cost:
Florida Estimate

TABLE I

Florida's Population 60+ Years Old[1]

	North West	North East	Central	South West	South East
Region Total	269,471	497,112	1,534,502	891,009	1,202,459
% of State	6.1%	11%	35%	20%	27%
% of Regional Population	18%	23%	24%	27%	21%

2010 Total Florida 60+ Population:	4,394,553
2010 % of Florida Population:	23%
2015 % of Florida Population:	30%
2015 % of National 60+ Population:	21%

TABLE II

US Average Body Weight[2]

	Adults	Child Age 1-5	Child Age 6-10	Child Age 11-15	Child Age 16-18
Females	166.2 lbs	20-40 (30) lbs	45 –74 (59.5) lbs	83-122 (102.5) lbs	125-127 (126) lbs
Males	195.5 lbs	22-42 (32) lbs	46-77 (61.5) lbs	88-137 (112.5)	145-155 (150) lbs

An average weight of **148.65 LBS** was used and found by first finding the mean of the weight of the minors. That number was included with the average female and male weights to find the mean weight of total patients.

Mean of minors' weight = 84.25; Mean of 166.6+195.5+84.25 = 148.65 LBS

TABLE III

Low THC Cannabis Compound Dosage by Weight & Condition[3]

	mg per lbs	Adult Male	Adult Female	1-5 yr old child	6-10 yr old child	11-15 yr old child	16-18 yr old child
Epilepsy	2-6 mg	391-1173 mg/day	332.4-997.2 mg/day	62-186 mg/day	121-363 mg/day	215-645 mg/day	276-828 mg/day
Muscle Spasms	3 mg	586.5 mg/day	498.6 mg/day	93 mg/day	181.5 mg/day	322.5 mg/day	414 mg/day
Cancer	10 mg	1,955 mg/day	1,662 mg/day	310 mg/day	605 mg/day	1,075 mg/day	1,380 mg/day

1. Office of Economic and Demographic Research. Data 2010 http://edr.state.fl.us/Content/area-profiles/2010-census-detailed-county/index.cfm, United States Census Bureau.
2. Center of Disease Control. http://www.cdc.gov/nchs/fastats/body-measurements.htm
3. Florida Office of Economic & Demographic Research—Revenue Estimate Conference pg. 660, 661

Medical Cannabis Production Cost:
Florida Estimate

Product Demand and Estimated Production Rate in Florida

	Daily Dose (Individual)	Monthly Dose (Individual)	Annual Dose (Individual)	Annual Needs (Total Likely Patient Pop)
Cancer	1,486.5 mg/ 1.5g	45,214 mg/ 45 g	542,573 mg/ 543 g	**3,216,875 g**
Epilepsy	594.6 mg	18,086 mg/ 18 g	217,029 mg/ 217 g	**737,899 g**
Muscle Spasms	445.95 mg	13,564 mg/ 14 g	162,772 mg/ 163 g	**1,534,977 g**

Total Annual Statewide Demand (CBD Oil): **5,489,751 g**

Total Raw Plant Needed (dried) to Meet Annual Statewide Demand (CBD Oil): **80,685.5 lbs** [1]

Annual Production Rate per Region (equally divided): **16,137 lbs**

1. Based on a 1:6.7 ratio of CBD oil extracted from dried cannabis plant (or 10-15%). This is a general figure as this ratio/percentage varies based on the strain.

Average Patient Weight:
148.65 LBS[1]

Dosage[2]:
Cancer - 10 mg/lb
Epilepsy - 2-6 mg/lb
4 mg/lb used
Muscle Spasms - 3 mg/lb

1. See Table II on previous page
2. See Table III on previous page

Cannabis Production Estimates

Caulkins, Jonathan P., Estimated Cost of Production for Legalized Cannabis, RAND Drug Policy Research, July 2010

Hawken, Angela Ph.D & Prieger, James Ph.D, Economies of Scale in the Production of Cannabis, Back of the Envelope Calculations Analysis Corporation, I-502 Project 430-5c, October 22, 2013. As of December 12, 2014: http://liq.wa.gov/publications/Marijuana/BOTEC%20reports/5c-Economies-of-Scale-in-the-Production-of-Cannabis-Final-Revised.pdf

Medical Cannabis Production Cost:
Florida Estimate

Estimated Cost of Production for Legalized Cannabis

By: Jonathan P. Caulkins ~ *July 2010*

2.4: Summary

Table 1 summarizes the considerations above concerning the production cost per pound of marijuana (specifically sinsemilla) for the three indoor production modalities.

Table 1: Estimated Post-Legalization Production Costs for Three Indoor Marijuana Production Methods

	5' x 5' indoor "hobbyist"	In a 1500 square foot residential house	1 acre 50% covered with greenhouses
Production Statistics			
Production Intensity (lbs/sq ft per yr)	0.42	0.42	0.21
Square feet cultivated	25	1300	21,780
Annual Production Rate (lbs)	10.5	546	4574
Cost per Pound Produced			
Materials (Exclusive of lighting)	$150	$50 - $150	$50 - $150
Lighting	$75	$75	$0 - $25
Labor Grow	In-kind Donation	$40	$10 - 25
Structure/Rent	In-kind Donation	$33 - $132	$10 - 15
Total cost per pound produced	$225 + In-kind	$200 - $400	$70 - $215

Caulkins Production Cost Estimate—Page 22 → **AS IT RELATES TO FLORIDA PRODUCTION NEEDS ESTIMATE:**

INDOOR TOTAL STATE

PRODUCTION STATISTICS
Production Intensity— 0.42
Square Feet Cultivated— 192,108
Annual Production Rate— 80,685.5
COST PER POUND PRODUCED
Materials (Exclusive of Lights—$50—$150
Lighting—$75
Labor Grow— $40
Structure/Rent— $33—$132
Per Pound Production Cost—$200—$400

GREENHOUSE

PRODUCTION STATISTICS
Production Intensity — 0.21
Square Feet Cultivated— 384,217
Annual Production Rate—80,685.5
COST PER POUND PRODUCED
Materials (Exclusive of Lights) - $50—$150
Lighting— $0—$25
Labor Grow— $10—$25
Structure/Rent— $10—$15
Per Pound Production Cost— $70—$215

It should be noted that Ben Burkhardt, owner and operator of HealthCentral and LivWell dispensaries in Denver, CO, one of the large scale growers and dispensers reached out to to gather data for this report stated that his production cost is roughly $600 per pound. He had an indoor cultivation operation. He also stated that a greenhouse cultivation operation will be about **half** the production cost of indoor oper-

Annual Statewide Production Cost:

$16,137,100—$32,274,200

Annual Regional Production Cost (equally distributed):

$3,227,420 - $6,454,840

Annual Statewide Production Cost:

$5,647,985—$17,347,382.5

Annual Regional Production Cost (equally distributed):

$1,129,597—$3,469,476.5

Medical Cannabis Production Cost:
Florida Estimate

Economies of Scale in the Production of Cannabis

Angela Hawken, Ph.D. and James Prieger, Ph.D.

Notable Graphs:

Figure 3: Indoor LRAC Curves, Three- to 30-Year Scenarios

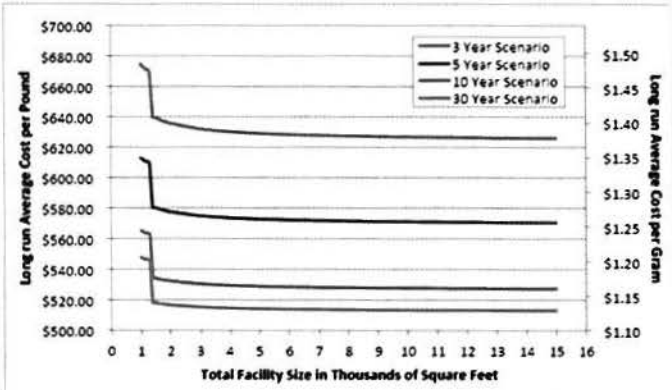


Figure 4: Greenhouse LRAC Curves, One- to 10-Year Scenarios

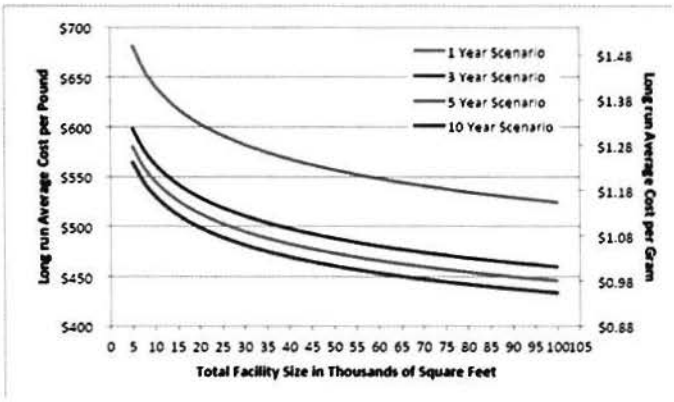
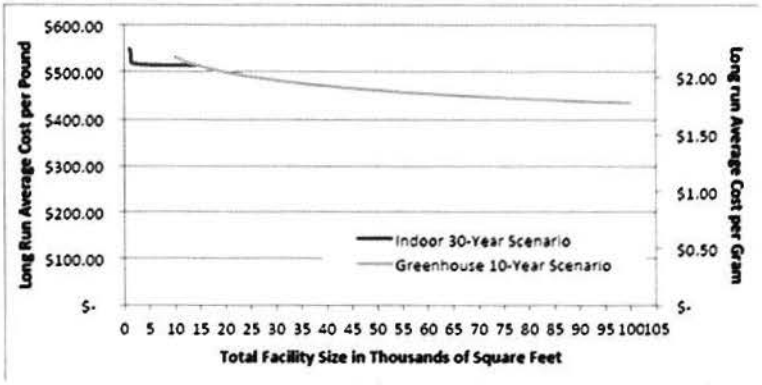


Figure 7: Indoor vs. Greenhouse LRAC Curves, Minimum-Cost Scenario



Medical Cannabis Production Cost:
Florida Estimate

The one million and six other costs to commence and run a large scale medical cannabis vertically integrated operation in Florida!

Extraction Machinery	Grower Recommended Machinery: Apeks High Production 5000 PSI Subcritical/ Supercritical CO2 Botanical Oil Extraction Systems. A larger grow operation may have up to six (6) of these machines.	**Price: $139,000 + Shipping. (X 6 = $834,000)**
Transportation Costs	Transport from cultivation facility to retail location. Transport from cultivation facility to individual patients (optional). Cost of vehicles including insurance, maintenance, gas, mileage and driver.	
Regulatory costs	Application fee, license fee, contracted work assembling application, renewal fee	
Retail facility costs	Staff, insurance, permits, taxes (if owned), rent/mortgage, utilities, equipment and security system, routine upkeep and sanitation, etc.	
Equipment Purchase	Lights, bulb replacement, watering systems, hydroponic equipment (optional), climate/environmental controls, safety equipment, lab equipment, sanitation equipment, computers, scanners, inventory software, mechanized trimmer(optional), labeling, production line, encapsulating, counting, sealing and packing machines, etc.	
Specialized Contractors	Requirement for at least two (2) medical directors, inventory agent(s), security specialists, potential need for compounding pharmacists, biochemists, professional pest, parasite and bacteria removal, IT specialists, electricians, marketing and advertising etc.	
Unusual & Unforeseen costs	Productivity set back due to inspection, insurance, $5 bond annual premium, legal and financial aide/representation, structural repair, machine Maintnance, plumbing, waste removal, lower income affordability program	

Bist, Kevin

From: cnaylor@flmca.com
Sent: Wednesday, February 04, 2015 4:53 PM
To: Nelson, Patricia A
Subject: RE: Production Cost Est.
Attachments: 5c_Economies_Scale_Production_Cannabis_Oct-22-2013BOTEC.pdf; Est Cost of Production for legalized Cannabis CAULKINS.pdf

Two interesting reports I reviewed and used for some data.

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BOTEC
Analysis Corporation

Economies of Scale in the Production of Cannabis

Angela Hawken, Ph.D. and James Prieger, Ph.D.

CONTENTS

I. What are economies of scale?
II. Why would regulators of legal cannabis production be concerned with economies of scale?
III. Description of project and goals
IV. Review of previous work on estimation of costs for growing cannabis
V. Description of data and methodology
VI. Estimated cost function
VII. Implications for the LCB

References

Tables

Economies of Scale in the Production of Cannabis

I. What are economies of scale?

Economies of scale is a term used to describe decreasing average cost of production (for example, the cost of producing a pound of cannabis) as a grower's total output increases. Economies of scale prevail if unit costs fall as output increases (if the elasticity of costs with respect to grower's output is less than one). Economies of scale might be realized either if there are diminishing marginal costs or if there are fixed costs of production (fixed costs such as capital equipment and plant construction are spread over a larger scale of output). Economies of scale might also result from improvements in organizational structure, productivity gains from labor specialization (with a higher output, workers can specialize more narrowly on specific tasks that they may better perform than if they devoted only a small share of their time to that task), and technology improvements. Members of the BOTEC team interviewed High Intensity Drug Trafficking Areas (HIDTA) staff in June. These discussions revealed that organized crime groups are running networks of houses and overseeing high-quality operations in terms of lighting, ballasts, layout, etc.[1] The organized crime groups are hiring professional electricians, professional carpenters, and more generally specialist labor at each step, as compared with the medical access point's providers who appear less sophisticated by comparison, with many doing their own construction and design (the consequence being a less sophisticated set up). We anticipate that I-502 will provide some external economies. Even today's small producers might be able to hire the sort of professionals currently employed by the organized crime groups, if only they are able to advertise and freely seek out that sort of professional help.

This paper focuses on *internal* economies of scale (the change in costs a grower would experience because of an increase in his output). Cannabis growers may also benefit from *external* economies of scale, in which increases in the output of an entire industry produce marginal cost savings for the entire industry, decreasing the average costs of production for many firms all at once. External economies of scale exist if growers benefit from being close to other growers. These may take the form of labor pooling, sharing common assets, better availability of intermediate inputs, and sharing know-how. An important external effect for growers might be shared enforcement risk (federal enforcement is more difficult as the number of growers increases). For some external economies of scale, it does not matter whether growers can communicate (e.g., for enforcement swamping) but for other external economies, what may matter is not only the total number of growers in

[1] There are Mexican gangs, for example, who are large outdoor producers, and do not fit this description. Production economies are quite different for indoor compared with outdoor growing. In this paper our interest is focused on indoor and greenhouse growing.

the area, but also the ability of those growers to trade information, expertise, share suppliers, etc. We do not model external economies of scale, but we provide some comment regarding the implications of external economies in our review of licensing options.

II. Why would regulators of legal cannabis production be concerned with economies of scale?

If economies of scale are present, estimating the magnitude of the scale effects is important for informing decisions regarding the optimal number of licenses to issue. If the economies of scale are very large, and persist indefinitely for larger and larger operating scales, then growers producing at a large scale might exclude small-scale farmers from successfully competing. Economies of scale therefore have implications for the number (and size) of growers that would be feasible in an unregulated market. This has implications for costs, price, product variety, and regulatory burden. Strong economies of scale would favor large growers, an oligopolistic market structure, and concentrated production; accordingly, they may strengthen the arguments for policies intended to mitigate those outcomes. Another reason to pay attention to economies of scale is that they affect the severity of an expected legalization-induced price decline, which in turn affects regulators' ability to drive the black market out of business as well as combat likely associated increases in use and abuse.

III. Description of project and goals

This paper examines the cost curves of cannabis production for indoor and greenhouse cultivation. Our particular focus is on assessing the size of economies of scale: does the average cost of production drop significantly as the producer becomes larger? An ideal analysis would involve observing organizations at multiple different operating sizes. This sort of data is not available. Instead, we observe separate costs for growers of different sizes and infer that the cost curve is the line that passes through these points. This approach is suboptimal but it is the best currently available way to estimate cost curves.

Drawing on data from previously published work and unpublished estimates from confidential sources, we generate cost curves for cannabis production that show how costs vary with scale. We also describe data from a new marijuana producer survey, and provide a summary of lessons learned from the 186 marijuana growers that were surveyed.

We then assess the impact of an increase in production volume (i.e., how much would costs fall if production shifts to larger producers) and provide estimates of the minimum efficient scale (the production quantity for which average cost is the lowest).

Finally, we assess industry costs under various licensing schemes (e.g., mandating a particular number of small producers), with the intent of determining if there is a minimum viable size for a producer.

IV. Review of previous work on estimation of costs for growing cannabis

The literature on the costs of growing cannabis can be grouped into three categories: cost estimates produced by advocates, industry promotion groups, or "how to grow" writers; unpublished or non-peer reviewed work that is nevertheless of academic quality; and peer-reviewed academic studies. Here we focus on examples of such work that we examined. This section is not meant to be an exhaustive review of the literature on the costs of producing cannabis. Instead, we combed through all the previous work we could find that were relevant for estimating economies of scale, and report those findings here. We also looked at work from the field of agricultural economics that, while not specific to cannabis production, concerned closely related crops and was therefore considered relevant for our discussion of economies of scale. We close this section with implications of the findings for our work.

A. Literature regarding cannabis production

Given the practical difficulties involved with conducting primary research on a largely illicit industry, much of the best-known and most heavily relied upon cost work is in the first two categories mentioned above. Our study relies heavily on the work of Caulkins (2010) and Denman and Cooley (2013) in particular, and we review those first.

1. Caulkins (2010)

Caulkins (2010) estimates production costs for legalized cannabis in three scenarios: a small and medium indoor growing operation, greenhouse growing, and outdoor farming in a "gray market" context (meaning no risk of arrest but nevertheless a requirement to remain subtle) and after enough time has passed for some technological innovation to have occurred (e.g., modest mechanization of trimming). While the report is not peer reviewed, it is one of the most highly cited papers in this area of research, and work relying on it in part has been published in peer-reviewed academic outlets (Caulkins *et al.*, 2011; Caulkins and Bond, 2012).

The main finding of Caulkins (2010) is that legalization may be expected to lower the wholesale price of cannabis dramatically in the long run, compared to then-current prices for the illicit product. This conclusion is based on two observations stemming from the calculations in the paper. First, even when considering the costs of growing cannabis in an inefficiently small indoor setting, the wholesale price for the illicit product is much higher than the apparent costs. Thus, either the production side of the industry enjoys a high degree of market power (monopolization) or there is a huge risk premium attached to the production process[2] (e.g., current growers pay even low skilled workers much more than is usual for farm workers, whereas Caulkins et al. presume the prevailing wage for farm workers would pertain). Given the

[2] See Caulkins *et al.* (2012, pp.37-38), for a brief, nontechnical discussion of the risk premium for producing cannabis.

apparently wide extent of illicit growing within and outside the US (see, e.g. Bouchard, 2008; UNODC, 2012),[3] the latter appears to be the more likely cause. To the extent that legalization at the state level reduces the risk of prosecution and seizure for producers of cannabis, this risk premium is expected to fall.

The second argument made in Caulkins (2010) for the expected decline in wholesale prices is based on production efficiency. The illegality of cannabis causes growers to make decisions about production aimed at minimizing risk rather than optimizing the production process based purely on agricultural and technical considerations. That is, an illicit industry will be structurally different than an above-board industry, with smaller growers than rationalization of production would otherwise demand.[4] Caulkins (2010) estimates that the cost per pound of cannabis produced is $225 for indoor micro-growing (with unpriced labor), $200-400 for a smaller indoor operation, $70-$215 for greenhouse growing, and less than $10 for large scale outdoor growing by professional farmers with modern farm machinery. While the quality of the product may not be the same across these scenarios, it is clear that if industry were to shift toward outdoor or even greenhouse growing that production costs would decline—perhaps dramatically—from current levels.

Caulkins (2010) speculates that economies of scale may exist in a few areas of the production process. Larger operations purchase materials in larger quantities, which may lead to quantity discounts from suppliers (p.4).[5] Larger operational scale also spreads out fixed set-up costs over more units of production, lowering average cost (p.4).[6] Finally, he notes that legalization may spur process innovation and increased automation into the production process (p.2).

2. Denman and Cooley (2013)

The most detailed cost estimation for production of cannabis is the work of Denman and Cooley (2013) (hereafter, "the Solstice report"). The Solstice report estimates the production cost for two indoor growing operations and one outdoor scenario. Their estimates, particularly for the indoor scenarios, are based on actual operations at facilities associated with Solstice. Many of their costs, such as the cost of obtaining building

[3] Production statistics for cannabis are understandably imprecise and subject to controversy in the field. However, as the following quotation from UNODC (2012) puts it, "[a]lthough estimates of the actual magnitude of cannabis production in the United States are lacking, eradication data point to continuing extensive cannabis cultivation in the country" [p.51].

[4] In the jargon of industrial organization economics, "rationalizing" an industry means adopting the industry structure that minimizes production cost. In many (but not all) industries, particularly those with heavy capital requirements leading to strong economies of scale, this means centering production in a few large firms (a tendency toward oligopoly).

[5] Note, however, that if such discounts were significant, we would expect that the industry (or a middle layer of purchasing agents) would organize collective purchasing.

[6] As we show below, this notion assumes either a short-run view of cost or a belief in strong economies of scale in long-run variable cost. For our analysis we adopt the long-run view and do not find evidence of strong economies of scale.

permits, are specific to the Seattle area. Instead of summarizing all of their work here, we will explain which of their assumptions and costs we use below in section V.B.

The Solstice report suggests the potential for economies of scale to be realized in a few parts of the production process. The authors mention that there are volume discounts for electricity for larger customers. They also suggest that equipment prices are lower for larger purchasers, although they mention discounts of only 2-5% (without specifying what scales of operation are being assumed in this regard or what thresholds would trigger the discounts).

3. Other academic studies

Bouchard (2008) derives a methodology to estimate total illicit production based on evidence from drug seizures and arrests for production of an illicit substance. The part of this work of interest to us is the regression estimates of the number of co-offenders per cannabis plant seized and how this figure varies with the type of operation. The results show that for each of the three cannabis growing modalities considered, indoor, hydroponic, and outdoor, a minimum of three individuals are involved on average. More interesting for the economies of scale issue is how the number of co-offenders varies with the number of plants seized. In a very crude way, this measure approximates the amount of labor required per unit of production (including trimmers' time, which under current conditions constitutes roughly 50% of total labor time, and is not subject to economies of scale because it is trimmed by hand).[7] For every additional 100 plants, outdoor growing is associated with 1.16 extra co-offenders, versus figures of 0.82 for indoor growing and 0.57 for hydroponic setups. Each of these estimates is statistically significant at the 5% level. If these figures were taken to apply exactly to labor productivity, they would indicate that there are economies of scale in the labor component of production.[8] However, since actual labor hours is not likely to be proportional to the number of co-offenders estimated from the statistical model, we do not build this assumption into our cost model.[9]

The findings also suggest that legalization may shift production methods away from hydroponic methods. The logic is as follows. First, legalization of cannabis production and the normalization of working in the field (in both senses of the term) may cause wages to fall (Caulkins,

[7] Caulkins' projections assume that with legalization, someone would figure out a less labor-intensive way to trim. Interviews with growers suggest they lack confidence that this sort of technology is likely in the near term.

[8] Bouchard (2008) estimates an affine relationship between the number of co-offenders and the number of plants seized. Finding a positive intercept term, which he does for all three production modalities, ensures that the average number of co-offenders ("workers") per plant is decreasing in total output.

[9] We are skeptical that the simple affine form of the model (linear in the number of plants and an intercept) would predict actual labor usage well at small scale. The model implies that to cultivate the first plant takes almost three workers. It is better to view the model as a linear fit to the data that locally approximates the actual relationship between labor and production in the region of the observed quantities.

2010, p.5). Then, as labor becomes relatively cheaper compared to equipment and materials, more labor-intensive methods of production become relatively more cost efficient. Per the regression results above, that means a shift away from hydroponics toward soil-based indoor growing. Countering this effect of legalization on lower wages, however, may be the additional costs of labor that would come to bear on a legitimate operation (payroll taxes, contributions to workers' compensation insurance, government-mandated healthcare costs, etc.).

A number of cautions are warranted regarding application of Bouchard's (2008) findings for present purposes. The data were from Eastern Canada, not the Pacific Northwest. Counting co-offenders is not the same as tallying the labor required as part of the production process, if only because there is no indication of how many hours of labor the co-offenders contributed to the actual growing process (if any). The production facilities that were discovered and raided may not be representative of the larger population of growers. Finally, the total number of observations is not large (less than 100). For these reasons we do not directly use these figures in our analysis, but they do suggest that the relationship between labor input and production output warrants a closer look than the simple proportionality that we assume below.

Fortenbery and Bennett (2004) examine the industry for the production of commercial hemp. The economics of producing cannabis for hemp differ from production for purposes of consumption, but given that similar (but not identical) plants are involved, some similarities are to be expected in the cultivation stage. Greater differences in methods and costs appear in the harvesting and processing stages. Fortenbery and Bennett (2004) note processing technology for fiber hemp is relatively labor and resource-intensive, making the potential profitability of hemp production in the US questionable. The processing of cannabis for marijuana has also been labor intensive (Caulkins, 2010). The more labor intensive an aspect of the supply chain is, the less it will contribute to economies of scale, as the amounts of labor required are typically proportional to the quantities of product involved. On the other hand, labor intensive production steps are more likely to undergo technological and process innovation and a longer-term increase in the capital to labor ratio (the potential for automated trimming being a good example).

We suspect that in the long run, legalized production and processing of cannabis will significantly reduce, perhaps drastically so, the amount of labor needed as the industry becomes more capitalized. That has been the trend in general agricultural productivity.[10] However, the mechanization of processing by itself does not necessarily imply economies of scale in the long-term perspective. Although capital costs may be fixed in the short run, leading to short run economies of scale as the fixed capital cost is spread out over more production, in the long run nearly all inputs are variable. Furthermore, even when large expensive machinery is required to minimize production cost, economies of scale do not always result (Kislev and Peterson, 1996), as discussed in the next subsection.

[10] In North America, agricultural output per worker rose from about $20,000 in 1963 to over $60,000 in 2003 (both in 2000 dollars). See Figure 8 of Pardey, Alston, and Ruttan (2010).

B. Literature from agricultural economics

1. Schumacher and Marsh (2003)

Ideal for our purposes would have been to find a high quality, peer reviewed econometric study estimating the cost function for cannabis production. No such study—or, indeed, any econometric study—exists of which we are aware. However, if, at least for our greenhouse scenario, we expand our product from cannabis to "plants grown in greenhouses" then we can draw on the excellent study by Schumacher and Marsh (2003). The authors surveyed producers in the floriculture industry with the intent of assessing economies of scale. They coupled their survey data on input usage and output with prices for labor, materials, and energy gleaned from various sources to estimate the industry cost function. They apply state of the art econometric techniques for estimation and inference to refine their model, and then derive the implied economies of scale. They report their results in the form of an elasticity. The elasticity of cost with respect to quantity produced ("cost elasticity"), a positive number, tells us in percentage terms how much cost rises when production rises by 1%. Thus, when there are no economies of scale, the cost elasticity is 1.0. If there are economies of scale, the cost elasticity is between 0 and 1. Their calculated cost elasticity is 0.827. This figure means that when output rises by 1%, costs rise by 0.827%, implying that there are mild yet non-negligible economies of scale in floriculture.[11] The 90% confidence interval for the cost elasticity is [0.822,0.831], indicating the high degree of statistical precision they obtained. It is important to realize that Schumacher and March's finding of economies of scale for floriculture is not driven by their assumed functional form for estimation; had their data been different, their same method could have led to a finding of diseconomies of scale, or no economies of scale at all. The nature of an elasticity makes it a particularly useful summary statistic for our purposes, since elasticities are unit-free and we need not consider differences in how cannabis and floriculture production are measured.[12]

2. Kislev and Peterson (1996)

We also searched for general perspectives on economies of scale in agriculture. Kislev and Peterson (1996) argue that significant economies of scale in agriculture are unlikely. As they explain, scale economies "usually stem from the lumpiness or indivisibility of fixed capital" but that in the long run, indivisibilities are hard to find on the farm. Tractors and other machinery come in virtually any conceivable size, from hobby size to behemoths purchased only by the largest multi-state agribusinesses. Furthermore, "in the few cases where large machines are the most

[11] The figure is calculated at the average values of output and input quantities in their sample, and thus is a summary statistic for elasticity.

[12] One factor that limits the usefulness of these estimates is the magnitudes of the scales involved. A relatively small-scale flower farm operates on a larger scale than a typical marijuana cultivator. You will not find any large economies of scale by observing existing small flower producers, for instance, because any producers too small to take advantage of a drastic economy of scale would have already been driven out of business.

efficient…rental markets develop." That is, contractual arrangements among farmers may be expected to arise to minimize cost in the industry, regardless of the size of individual producers.

Another potential indivisibility is with labor. This arises in our context below with management labor for small operations. Kislev and Peterson (1996) point out, however, that potential indivisibilities in agriculture are smoothed out by options such as part-time farming and judicious use of seasonable agricultural labor for hire. Kislev and Peterson (1996) conclude "among the conventional inputs of land, labor, and capital, long-run indivisibilities should not be given serious consideration as a source of economies of scale."

It is hard to reconcile these conclusions with the observed domination of American agriculture in the heartland by giant farms of 1,000+ acres. Some of the consolidation into large-scale operations might be explained by the professionalization of operations for large versus small-scale farmers. And agricultural machinery is becoming increasingly more computerized. A GPS satellite positioning system and a computer guided planter, for example, cost the same on a small or a big tractor

C. Implications for economies of scale

Synthesizing the literature reviewed above, we conclude that while there are potentially some areas of cannabis production that exhibit economies of scale, 1) no one has yet performed calculations to directly assess them, and 2) we should maintain a healthy skepticism toward finding significant economies of scale. A few specific finding from the literature affected our calculations more directly. In section V.B.2.d) below we followed up on Denman and Cooley's (2013) assertion regarding quantity discounts for electricity, and found that they have the potential to create relatively large economies of scale at the low end of the scales of operation we consider. Drawing on the ideas of Kislev and Peterson (1996) described above, we will treat management labor as fully scalable, along with other types of labor. In this we depart from some of the other cost estimates performed in this area (e.g., the Solstice report).

For our greenhouse growing scenario, given the paucity of available data specific to cannabis production, we will instead rely heavily on the cost elasticity estimate of Schumacher and March (2003). See section V.B.3) There is some tension between Kislev and Peterson's (1996) contention that there are no great economies of scale to be expected in the long run in agriculture and the thoughts of our survey respondents on the one hand, and our use of Schumacher and Marsh (2003) cost elasticity on the other. We take a middle course between these two poles by splitting the difference and using an assumed cost elasticity of 0.913 instead of Schumacher and Marsh's (2003) estimate of 0.827 or the elasticity of 1.0 that would obtain under no economies of scale. We recognize that these estimates are not ideal, in that they derive from other crops and from mature industries, whereas legal marijuana is a brand new industry, but they offer a starting point for our analysis.

V. Description of data and methodology

In this section we describe our data and how we make use of it. Our goal is to estimate costs for two scenarios: indoor production with artificial lighting and greenhouse growing. For simplicity we refer to the former as the "indoor production scenario", even though greenhouses are not outdoors.

A. Data

We draw assumptions and data from three main sources for our work: Denman and Cooley (2013) (the Solstice report), Caulkins (2010), and Schumacher and Marsh (2003). Our original intent was to use primary data from our new Marijuana Producer Survey, but we did not receive enough survey returns within time to construct our models and had to rely on other sources for model development. The first two of the above sources are bottom-up accounting estimates of production costs for producing cannabis. Each is created using the authors' detailed knowledge of the production process and the costs it entails. Neither, however, focuses mainly on economies of scale, our primary issue. Schumacher and Marsh (2003) on the other hand, as described above in the literature review, take economies of scale as their main interest and estimate a cost elasticity for greenhouse growing (for floriculture, the growing of flowers and plants for sale to nurseries and other retail outlets).

We use the Solstice report, supplemented by Caulkins (2010), to estimate the production cost of indoor growing under artificial lighting at various scales.[13] Similar to their work, we build this part of our cost model from the bottom up, with detailed calculations involving wages for various types of work, the prices of plants, materials, and equipment, likely relationships between inputs and output, and fixed costs such as rent and insurance. The Solstice report provides two estimates for indoor growing: a 1,500 square foot (sf) facility and a 10,000 sf facility.[14] Their data have the twin advantages of coming from active, current operations and being specific to the Seattle area. They did not consider greenhouse growing.

We have since compared the results of our marijuana producer survey to the other sources. The results of the surveys returned are in line with those produced by the other authors, and we use them to verify inputs.

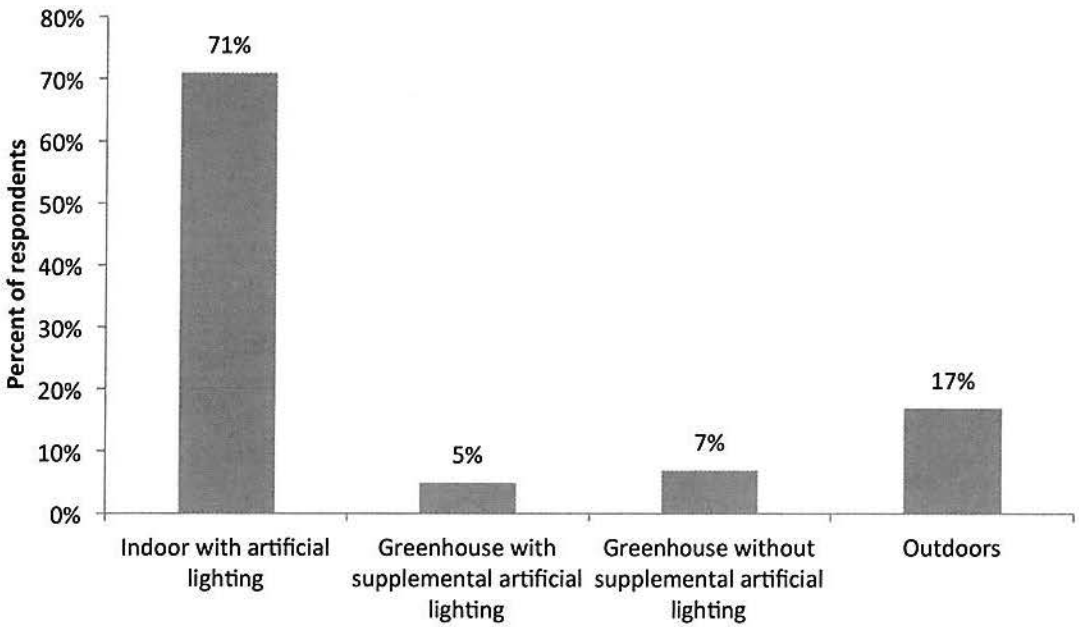
Description of sample:

[13] An important difference between estimates produced by Caulkins and those produced by Solstice is Solstice provides estimates of current production costs, whereas Caulkins models likely future costs after innovation has permeated the industry.

[14] The facilities from which the production and cost figures are calculated were actually 1,000 sf and 14,000 sf in size. The report's authors adjusted the numbers so be applicable to 1,500 sf and 10,000 sf.

We have responses from a total of 186 marijuana producers. Responses were solicited through a trusted network. Figure 1 describes the type of cultivators included among the respondents.

Figure 1: Marijuana Producer Survey Respondents: Type of Cultivation



Growing operations varied significantly on scale. The size of outdoor grows ranged from 50 to 200,000 square feet (with an average size of 11,000). The size of indoor grows ranged from 20 to 30,000 square feet (with an average size of 980).

1. Implications for the indoor production scenario

We carefully examined their figures and calculations, with a particular eye toward identifying where the costs of running the larger facility were less, in proportional terms, than the costs of operating the small facility. Analysis of the survey responses showed that many parts of the relationship between the scale of the indoor operations and cost are indeed likely to be proportional. For instance, short-run variable costs

such as labor for trimming, water, soil, CO_2, nutrients, and pesticide scale up and down directly with the size of the operation.[15] Moreover, many of the costs that are considered fixed by the Solstice report, such as equipment (e.g., for cultivation, lighting, and nutrient delivery), genetic stock for startup, rent, insurance, and management and general labor, appear to be proportional to scale.[16] Some of the components contributing to the assumed construction of the facility (design, plumbing,[17] and carpentry costs, in particular) also are in proportion to scale, or nearly so.[18]

There are a few sources of economies of scale we found in the Solstice report. The electrical and HVAC work required many fewer hours/sf for the larger facility than for the smaller. The fees for the construction permits are also sublinear in project size. However, the latter parts are relatively minor components of overall cost, and so do not create strong economies of scale in the indoor production process.

Unexpectedly, there are two sources of diseconomies of scale in the Solstice figures: security system installation (for which the diseconomies are mild) and general contracting hours in the construction of the facility. The latter is problematic for our purposes, because the larger facility is only 6.7 times larger than the smaller operation, yet is assumed to have 30 times as many hours needed for general contracting. Presumably their figures in this regard are driven by idiosyncratic features of the actual facilities constructed from which they drew their numbers; there is no apparent reason why every larger facility should require so much disproportionate effort in general contracting when no similar diseconomies are found in any other component of the construction costs. We also examined preliminary survey results on startup costs (*int. al.*) from other BOTEC consultants (Zamarra, 2013), and while we found considerable variation in costs per sq. foot, particularly at the lower end of the size spectrum of those surveyed, there was no indication of such huge (or indeed, any) diseconomies of scale. Thus, we did not rely on the Solstice figures as is, but instead assumed the general contracting hours were proportional to scale, in the absence of better information (details are contained in the next section).

[15] We found no evidence that growers on the large end of our scale would be able to command discounts on input prices; large indoor cannabis growers are still small compared to other agricultural establishments in general. By comparison, about one-quarter of floriculture greenhouse growers are larger than 500,000 sf (Mateo, 2008).

[16] Such costs can be properly viewed as fixed in the short run but variable in the long run, which we explain further below.

[17] The Solstice report contains what appears to be a typographical error in the plumbing hours for the larger facility. The report states 40 hours are needed for the 10,000 sf facility, whereas 60 hours were needed for the 1,500 sf facility. If the 40 were actually 400, however, then the figures are directly proportional to size. We assumed 400 was actually meant.

[18] All references to "construction" for the indoor facility refer to modifying an empty warehouse space. Costs for the construction of the warehouse or bare industrial space itself are assumed to be included in the rental charges.

We identified two additional sources of economies of scale for the indoor scenario: the LCB license and the discounts available in electricity tariffs for larger scale operations. In our analysis, we use LCB's announced renewable license fee of $1000.[19] If someone has two licenses (producer and processor) then this would be doubled. The flat fee mirrors LCB's license fees for liquor sales, it appears that the practice is to set a single fee for a license for a particular type of establishment, but not to vary the cost of the license within an establishment class by retail volume or sales.[20] On the production side of the liquor market, LCB license fees do vary by scale in some cases, but only very coarsely. For example, wineries producing less than 250,000 liters per year pay $100 for their license, while larger wineries pay four times as much. For our calculations we assumed that the LCB would charge a fee of $500 for indoor production and twice as much for greenhouse operations, which we generally expect to be larger. These fees, while arbitrarily assumed, are higher than charged for craft distillery licenses ($100) but less than brewery licenses ($2000), which roughly span the charges for licenses. The nature of an annually recurring fee is that of a fixed cost, even in the long run. As such, it will contribute to economies of scale even in our long run analysis.

In the indoor production scenario, the other source of potential scale economies that we added (beyond the Solstice analysis) is quantity discounts for electricity.[21] We examined tariffs from Seattle Light and Power, the electricity utility in the Seattle area, and found that for commercial customers on a particular tariff (small or medium), there are no quantity discounts. That is, both of the two relevant tariffs (those for small and medium size business customers) have a single price for electricity demand and usage, but the medium-size tariff is significantly cheaper than the tariff for small business customers. The quantity discount comes from creating enough demand load often enough during the previous billing year to qualify for the medium-size tariff. The threshold is 50 kW of demand, which may be lower than the demand of the smallest of the facilities we consider (our analysis extends down to 1,000 sf indoor operations). If that were the case, then these smallest operators would face a significant disadvantage in electricity prices. Since electricity usage is a major cost for indoor cannabis growing, scaling up to take advantage of the more advantageous electricity tariff create nontrivial economies of scale at the low end of our range. Based on the figure for electricity usage in the Solstice report, we estimate that the 50 kW demand threshold is met when the indoor facility size is 1,350 sf.[22]

[T]There is also a one-time $250 license application fee.

[20] For example, beer and wine specialty shops, which may be expected to have smaller sales volume than grocery stores, pay $100 for a liquor license in Washington, regardless of the size of the shop, while grocery stores pay $150 (Washington State Liquor Control Board, *Retail Liquor License Endorsement Description and Fees Information*, available from http://liq.wa.gov/publications/licensing/LIQ_180_Retail_Desc_Sheet-6-14-12.doc (as of June 1, 2013)).

[21] The Solstice report mentions price discounts for electricity, but assumes all facilities will be large enough to qualify.

[22] The calculation assumes a demand load of 37 watts per sf of total facility size. We arrived at this figure by examining electricity costs in the Solstice report. The figure is in accord with Caulkins' (2010) figure of 40 watts per sf and is at the upper end of the range implied by a "growers' rule of thumb" in Bouchard (2008). That rule of thumb is that one 600- or 1000-watt metal halide/HPS amp will produce one pound of cannabis. Working through the figures for our scenario, that rule implies a total demand load of 32.3 (with 600 watt lamps) to 53.9 (with 1000 watt lamps) for our 1,500 sf facility, which in turn equates to 22 to 36 watts per sf of total facility size.

While this particular threshold is specific to one utility, several other utilities in the state offer similar price structures, albeit with other thresholds and rates.

2. Implications for the greenhouse production scenario

For greenhouse growing of cannabis, finding detailed cost information comparable to the Solstice figures for indoor production was very problematic. For that reason we do not attempt to estimate economies of scale from a detailed, bottom-up estimation of the costs of running various sizes of operations. Instead, we estimate the costs involved in running a greenhouse facility of typical size, which we take to be an acre of rented farmland housing a greenhouse occupying 75% of the space (yielding about 33,000 sf of greenhouse footprint). We chose this as our typical size as a compromise between typical greenhouse sizes in the cannabis and other agricultural industries. (Though 33,000 sf may be on the high end of current greenhouse cannabis operations, it is actually on the low end for greenhouse operations producing flowers, vegetables, and fruit.) By comparison, floriculture establishments averaged about 302,000 sf on the West Coast (Evans, 2002). Our greenhouse construction cost estimates come from a variety of sources, as we explain further in section B.3

Given this baseline size and its estimated costs and output levels, we drew on the work of Schumacher and Marsh (2003) to inform estimates for the cost curve at other production levels. As mentioned in section IV.C, we made use of these authors' estimated cost elasticity by taking the midpoint between their estimate of mild economies of scale and no economies of scale. We then fit a variable cost function possessing this elasticity and passing through the quantity and cost estimated for our typical greenhouse. Additionally, we add the LCB license fee and security monitoring on top of the estimated variable cost curve. Thus, considering our lack of detailed data on greenhouse cannabis production at various scales, we instead use Schumacher and Marsh's sophisticated econometric estimate of cost elasticity, calculated from a large sample of actual greenhouse growers of somewhat similar crops (flowers and plants). The results are meant to be illustrative, and can be refined as additional cost data on greenhouse growing of cannabis become available.

B. Methodology and assumptions

In this section, we describe our approach for synthesizing data from multiple sources and methods for converting accounting costs into economic costs. Our analysis rests on the notion of *long-run average cost* (LRAC) from economics. In economics, analysis of the costs of using scarce resources—be they labor, materials, money sunk into capital, or managerial expertise—includes considering what the decisionmaker gives up by not making an alternative choice. Thus, economic costs are opportunity costs—the value of the best forgone alternative when the choice to use a resource is made. While the accountant's and the economist's definition of costs coincide for many items, such as wage labor and consumables like materials, the treatment of the costs of durables, unpriced inputs such as owner-supplied management, and rental

deposits differs. To perform the long-run industry analysis appropriate for evaluating various licensing scenarios, we adopt the economist's approach.

In the work that follows we will consider scenarios with various time horizons: one, three, five, and ten years. For the indoor scenario we additionally consider a 30-year horizon (the horizon that minimizes LRAC, given the assumed life of capital and equipment, as explained in section 1.b) below).

1. Methodology

While the details of the costs we include are contained in the following subsections, we describe here the main points where the accounting and economic treatment of costs differs. We also discuss how our approach to costing differs from a traditional discounted cash flow (DCF) analysis.

a) Opportunity costs in the models

There are three cost elements in our work where economic costs are treated quite differently than accounting costs: the opportunity costs of capital and other durable input goods, unpriced contributions of labor, and the value of money tied up in rental deposits.

The rental rate of capital, also known as the user cost of capital, is the opportunity cost of having a business' investment money tied up in structures, machines, and equipment instead of in another investment earning the currently available rate of return. A standard formula from microeconomics shows that the user cost of capital, expressed as a rate per dollar of capital, is equal to the sum of depreciation and the return that would be earned on similarly risky investments. That is,

$$r = d + i$$

where r is the rental rate of capital, d is the rate of physical and financial depreciation, and i is the rate of return on similarly risky ventures.[23] The economist's treatment of depreciation is the decline in the market value of an asset during a period.[24] That decline in value stems from two sources: the physical diminution of the capital stock due to machines wearing out and the pure change in value due to price depreciation.

There are two capital asset classes in our model: 1) the initial construction of the facilities and 2) the durable equipment used for cultivation, environmental and lighting control, nutrient delivery, and finishing. For the capital embodied in the facility construction itself, we treat the

[23] See, for example, equation 23.16 of Nicholson (1989).
[24] This may be quite different than the IRS depreciation rates used for tax purposes by accountants.

indoor facilities differently than the greenhouse facilities. The Solstice report shows that indoor facilities require a great amount of purpose-driven construction work to repurpose a bare warehouse space into a production floor for growing cannabis. Given the highly specific nature of these alterations, we have made the assumption that there is no market resale value to the improvements. That is, we treat the construction cost for indoor operations as a *sunk cost*—none of the construction cost is recoverable should the business attempt to cash out and leave. While this assumption is extreme, we adopt it for the following reasons. First, the sunk nature of the cost most heavily influences our shorter-term scenarios. Once the horizon of the economic analysis extends to or beyond the lifetime of the capital, capital cost becomes one more recurring cost. Second, we envision in our short-term scenarios (say, the one and three year scenarios in particular) that the reason the business is closing up so quickly is due to federal intervention and seizure of assets. If that were the case (and all that matters is that this would be the firm's *ex ante* expectation of why they would close so quickly), then there would presumably be no opportunity to sell the structure with its cannabis-production-specific improvements to a similar outfit. Although the value of the construction capital depreciates 100% immediately, that reflects price depreciation instead of physical depreciation. For the latter, we set the capital life to 15 years, based on IRS assumptions for agricultural and horticultural structures.[25]

For greenhouse construction, on the other hand, a valuable fraction of the total investment is the greenhouse itself, which may have value when put to other uses.[26] Therefore we do not assume that greenhouse construction is a fully sunk cost. Instead, we assume that only 50% of the value depreciates immediately, and the remaining value decreases linearly (straight-line depreciation for the remaining value) until the end of the life of the capital. Instead of using a 15-year life for greenhouses, in line with the general IRS assumption for agricultural and horticultural structures, we reduced the useful life of a greenhouse to 10 years. This reflects the fact that many modern greenhouse are not the "walls of glass" that often come to mind with the term (known as a "glasshouse" in industry parlance), but instead are structures covered with translucent or transparent plastic sheeting. The life of the plastic sheeting may be as brief as three years (WVUES, 2013), depending on the material used, even though the metal ribbing of the structure lasts far longer. Ten years is our compromise figure.

Both indoor and greenhouse production make use of durable equipment such as fans, temperature regulators, and nutrient delivery tubing and pumps. Since much of this equipment would have legitimate use in many other agricultural and industrial applications, we assumed that only

[25] In particular, 15 years is the "class life" for any "single purpose agricultural or horticultural structure," per IRS Pub. 946, chapter 4 (2012).
[26] The thought may occur to the reader that, by similar logic, the warehouse itself may have resale value in the indoor growing scenario. However, along with Solstice we assume the warehouse is rented, not purchased, and therefore the "resale value" of the warehouse is embodied in the rent and need not be considered separately in the analysis.

50% of its value is sunk.[27] As with the greenhouse capital embodied in the structure, we take a straight-line depreciation for the remaining value until the end of the useful life of the equipment, taken to be 10 years. The latter figure is chosen in accord with IRS assumptions for agricultural equipment.[28]

Given that cannabis production represents considerable legal risks even under the I-502 market, *i* (the rate of return on similarly risky ventures) represents not just the interest rate but also an upward adjustment to account for the additional risk. We choose *i* = 10%, but this parameter can be easily varied in the analysis. This rate reflecting the opportunity cost of sinking money into capital is applied to the undepreciated value of the capital remaining midyear. For example, in the one-year scenario, since indoor construction fully depreciates right away, there is no midyear value, and the rate *i* is applied to a value of zero yielding zero opportunity cost. Conceptually, this is because with sunk costs there is no opportunity to sell the asset and use the money elsewhere. For equipment or greenhouse construction, on the other hand, the value remaining in the middle of the first year is 50%, and the opportunity cost associated with that value is therefore 0.5*i* times the original cost of the asset. In scenarios with longer horizons, conceptually the treatment of years after the first year is similar: rate *i* is applied to remaining midyear value.[29]

b) The long-run average cost approach (LRAC) vs. discounted cash flow (DCF)

Our methodology is aimed at estimating long run economic costs. One reason for the focus on the long run is that we are interested in questions of the sustainability of particular industry structures under various licensing schemes. Another reason is that by looking at the long run, certain costs that are fixed in the short run become variable in the long run. Examples of such costs are those that the Solstice report call "fixed costs": rent, insurance, security monitoring, and labor categories of management and general farm work (not including trimming). In a short-run sense, these indeed are fixed, as they do not vary directly with the size of the harvests, *given that* 1) a lease on a particular size building is in place, 2) insurance has been purchased for a six-month period, 3) a manager shows up for work every day regardless of last month's plant growth, and so on. However, in the long run all these can be treated as variable costs—appropriately sized buildings and structures can be rented or built to accustom changes in planned production changes, just as insurance policies and management talent (and

[27] Our intent in immediately depreciating 50% of the value of equipment is to reflect 1) the change in market value of "new" versus "used" industrial equipment, even when the latter is fairly new, and 2) the costs that would be entailed in finding a buyer for the used equipment, uninstallation, shipping costs, etc.

[28] In particular, 10 years is the class life for "agricultural machinery and equipment," per IRS Pub 946, chapter 4 (2012).

[29] We simplified this procedure in one respect for purposes of simplifying the calculations for scenarios with horizons greater than one year. Instead of applying rate *i* to actual midyear remaining asset value, each year after the first we apply it to the *average* of the midyear values that obtain during the remainder of the scenario. This simplification affects the calculations only a small amount, and (most importantly for present purposes) does not alter the overall shape of the LRAC curves.

therefore cost) can be reworked as the scale of the operation changes, and so forth. Thus where other analyses have distinguished between variable and fixed costs on the basis of whether they vary with production during the year, we instead refer to the former as short-run variable costs and the latter as long-run variable costs (as shorthand for "costs that are fixed in the short run but varying in the long run"). In the long run, the only truly fixed—that is, scale-independent—cost is the assumed cost for the LCB license.

Given our interest in assessing costs and prospects for the industry as a whole, the long run economic approach is warranted. However, certain aspects of our methodology may appear unusual to those schooled in traditional MBA-style discounted cash flow (DCF) analysis. In a DCF analysis, the costs and payoffs over the life of investment are discounted to present value, and the project is deemed worth taking on if the net present value is positive. In contrast, our method does not convert expenditures and revenue to present value. Instead, we treat the length of the scenario under consideration as a single time period, aggregate the costs, divide by the total production in the period, and finally divide the former by the latter to arrive at long-run average cost. By abstracting away from the details of net present value at any particular point in time over the life of the capital and equipment, we are able to average out the fixities in (i.e., the "lumpiness" in costs for) construction, capital, equipment, depreciation, and labor. Furthermore, given long enough horizons, we can treat sunk costs as recurring costs. This is the standard approach in, for example, regulatory economics and accounting for industries with long-lived capital, such as telecommunications and electricity. Thus we will extend the horizons of our modeling to the minimum number of years required for all capital and equipment to simultaneously reach the end of its expected lifespan. This requires a horizon of 30 years for the indoor scenario (the lowest common denominator of 10-year equipment and 15-year facilities) and 10 years for the greenhouse scenario (the life of both facilities and equipment). Scenarios with the longest horizons minimize LRAC for any given amount of production, because all productive use of the capital has been wrung out of it.[30]

Finally, we note that our economic approach glosses over many considerations that a small operator may be forced to deal with in actuality. We assume that the financial capital markets function smoothly, so that money can be found to finance startups at our assumed rate of *i*. However, given that we have risk-adjusted *i* to be on the high side, we at least implicitly subsume some financing problems. [31]We also do not consider any additional problems producers might have in procuring production or agricultural space, for instance if landlords and landowners prove to be reticent to rent to cannabis producers. Furthermore, we set aside any speculation about unequal rates of inflation across the

[30] Remember that our assumed depreciation is front-loaded. This means that most of the economic cost of the asset is "paid" near the beginning of its life, which in turn means that the asset is relatively inexpensive to use at the end of its life.

[31] A risk-adjusted interest rates seems justified given the risks involved in investing in the marijuana industry. Our survey showed that access to capital presented an important challenge to many marijuana growers and for many it was an impediment to increasing the size of their operation.

classes of goods, services, and inputs that are relevant to costs and revenues of growing cannabis. Instead, we treat real prices as unchanging in all scenarios, regardless of horizon.[32]

2. Assumptions and costs for the indoor production model

To compute average cost for the industry, we must make explicit the link between inputs and outputs. That is, we must posit a production function. Then we must estimate cost. Production cost in our scenarios stem from four sources: capital costs, long run variable costs, short run variable costs, and the long run fixed cost of the LCB license. In this section we describe the production process we assume and break down each of the types of cost for the indoor production scenario.

Before proceeding, it is important to recognize two things at the outset. First, as with other work in this area, we are forced to make assumptions about many aspects of the production process and the costs associated with production. While we make our best efforts to use reasonable values in all cases, there will be an inescapable amount of approximation error in our final results. Second, and more importantly for our present purpose of assessing economies of scale, the *shape* of the cost function is more important than its *level*. Changing many of our assumptions would change the level of the average cost function—i.e., shift it vertically—without changing its shape (or changing it little). However, it is the shape of the average cost function that determines whether there are economies of scale.

a) Production

We must first make clear our assumptions regarding the usage of the space rented. After reviewing similar work by others (Caulkins, 2010; the Solstice report) we settled on the assumption that 70% of the total space rented is used for production, with the balance being dedicated to offices, bathrooms, breakrooms, and the like. Of the 70% devoted to production, only 70% of that space is used as growing area ("canopy"), with the other parts of the production floor set aside for walkways, etc.[33] Thus, for example, in the 1,500 sf facility, about half of the space (actually 49%, or 70%*70%) is used for canopy. However, since the relationship between growing space and total space is assumed to be proportional (at least within the range of sizes considered in the scenarios), costs that are proportional to canopy area are also proportional to total area, and vice versa.

[32] General inflation that affects all costs and revenues of production equally has no impact on our analysis, since an economic analysis is always conducted in real (inflation adjusted) prices.

[33] We suspect that setting aside 30% of the growing floor for walkways is overly generous compared to current illicit and semi-licit operations. However, with legality will come adherence to OSHA and other state, county, and city rules on safe and appropriate industrial layout, which will presumably lead to less crowded production floors.

We take production numbers exclusively from the Solstice report. Based on actual production numbers from their sources, their 1,500 sf facility produces an average of 8,148 grams (nearly 18 pounds) of cannabis per month. This amount comes from an assumed four harvests per year and each plant occupying nine sf. The total annual product represents 5.4 grams per sf of total space. To allow comparison with other production estimates, note that the Solstice report implies 33.26 grams (or 0.073 pounds) per sf of canopy *per harvest*. In contrast, Caulkins (2010) cites studies a study from the Netherlands from small indoor growing operations showing production averaging 0.105 pounds per sf of canopy per harvest. That difference is likely accounted for by the fact that the plants in that study (Toonen *et al.*, 2006) were planted much more densely than the Solstice report assumes—1.4 plants per sf in Toonen's study and 1 plant per 9 sf in the Solstice calculations. In a more recent survey of production studies, Caulkins (2013) summarizes the evidence as pointing toward 40 grams (or 0.088 pounds) per sf per harvest for indoor growing. To facilitate comparison with other studies, we will also state the yields from the Solstice report in various other metrics: 0.073 pounds per sf of canopy per harvest, 133 grams per sf of canopy per year, 65.2 grams per sf of total facility space per year, 93.1 grams per sf of production space per year, 0.14 pounds per sf of total facility space per year, and 0.66 pounds per plant (per harvest).

Given that our production numbers are a bit lower than these other estimates, we briefly consider here the impact of our assumptions. If production volumes were higher, then it would have the effect of lowering average capital cost and some components of average variable cost. That is, higher amounts of production could result from employing the same amount of capital or bearing the same level of certain long run variable costs (such as rent and management), thereby lowering these variable costs per sf. On the other hand, short run variable costs that are proportional to output (such as electricity and trimming labor) would remain unchanged in average terms. Finally, long run fixed costs would fall in average terms. Given that the economies of scale we identified above are generally found in capital costs and long run fixed costs, underestimating production therefore has the effect of overstating potential economies of scale. However, since we generally find only mild economies of scale in indoor production, it does not appear that modest increases to our production figures would change our conclusions.

b) Capital cost

Here, the term "capital" applies to construction costs, equipment, and initial genetic stock. These are the start-up costs from the Solstice report, with two modifications. First, in scenarios with horizons that leave some capital less than fully depreciated, the full cost of capital is not included. Second, as described above, we included the opportunity cost of the money invested in undepreciated capital. Total value of capital before any depreciation is in Table V.1. This and subsequent tables show costs for two facilities, in the same sizes as the Solstice report: 1,500 and 10,000 sf. It is important to realize, however, that we calculate these costs as a function of facility size, and assume that our calculations

are good for any indoor facility between 1,000 and 15,000 sf.[34] Unless otherwise noted below, for each of the line items in Table V.1 we assume that cost can be linearly interpolated and extrapolated across the 1,000 to 15,000 sf range, based on the costs calculated for the 1,500 and 10,000 sf facilities.[35]

The first component of capital cost is for construction: rendering bare warehouse space into a production floor. The labor categories and hours listed in Table V.1 are taken directly from the Solstice report (but see footnote 17), with the exception of general contracting. As mentioned above, we found it best to modify the hours required for general contracting to avoid the implied huge diseconomies of scale in the Solstice hours. Instead, we used Solstice's numbers to calculate the linearly interpolated number of general contracting hours for a 5,000 sf facility, and then assumed that general contracting costs were proportional to facility size. The wages for the construction categories are median values for Washington State, available from a spreadsheet from the Washington Employment Services Division.[36] Since what customers pay for construction work is more than the wages paid to construction employees, we followed Solstice in arbitrarily marking up wages 200% to account for payroll taxes, benefits, overhead, materials used in construction, and profit.[37]

Construction costs include both labor and building permits. The exact cost of such permits will depend in which city or county the facility is constructed. We followed Solstice in assuming a Seattle location but recalculated their permitting costs assuming the work would be treated as renovation (rather than construction), since the basic industrial space is assumed to be rental of an existing structure. Unlike the other

[34] We chose not to extrapolate the indoor figures beyond that range because doing so would take us too far from the Solstice sizes upon which we base most of our calculations.

[35] The assumption of linear interpolation does not by itself create economies or diseconomies of scale, because linear interpolation of cost between the two scales of operation implies that cost is affine (not linear) in square footage, and therefore not necessarily proportional to the scale of operation.

[36] The spreadsheet is *Washington Statewide 2012 Occupational Employment and Wage Estimates*, which includes all counties) These do not necessarily match those from the Solstice report, either due to more recent wage data or choice of different occupational categories. We matched the occupation in the Solstice report to the closest category in the WA ESD spreadsheet. Those categories that weren't exact matches it occupation were: general contracting (for which we used wages for "general and operations managers"), design ("commercial and industrial designers"), and HVAC professional ("heating, air cond, refrigeration mechanics & installers").

[37] Although the Solstice report says wages are marked up 150% in their calculations, examination of the actual figures and the tables in the appendix shows that they actually used a markup of 200%.

components of cost in Table V.1, the fees for the building permits are not interpolated, but are calculated using a fee calculator from the Seattle Dept. of Planning & Development for every possible facility size.[38] The fee structure displays some economies of scale.

The second component of capital cost is for equipment. The categories and costs for equipment are taken directly from the Solstice figures for the 1,500 sf facility, and are assumed to be proportional to facility size.[39] A tacit assumption underlying proportionality is that over the range of facilities considered here, the discrete nature of some of the equipment is not important[40] and that larger facilities will not be offered purchasing discounts beyond what smaller facilities receive, as discussed above.

The third component of capital cost is for the initial stock of cannabis plants with which to begin production. Here, we defer to the expertise of the authors of the Solstice report and their grower contacts, and assume the same sizes, quantities, and types of plants will be needed to begin operations. Given the assumed "perpetual harvest" model in the Solstice report, these include potted cannabis plants of various sizes (including some larger, more expensive plants to hasten the time to first harvest) and rooted clones. After the initial expenditure on plants, we assume that the future needs for genetic stock are self-supplied through propagation. In the absence of other information, we do not assign a cost to such propagation, beyond that priced in the labor components of operations (below).[41]

The total values of capital installed at startup average $68.34/sf for the 1,500 sf facility and $64.99/sf for the 10,000 sf facility. These estimates appear to be in line with preliminary surveying of costs performed by other BOTEC consultants (Zamarra, 2013). Out of seven usable survey respondents, six reported startup cost per square foot of $57 to $71 (there was an additional outlier of $131), for a trimmed mean of $66.50.

[38] The spreadsheet is titled "Fee estimator (based on 2013 Fee Schedule)", from http://www.seattle.gov/dpd/cms/groups/pan/@pan/documents/web_informational/dpdd017615.xls. We entered the total figure for the value of the construction work as the value of alteration to an existing structure in the calculator.

[39] Here we depart from the Solstice report, where the authors multiplied the equipment costs from the smaller facility by a factor of 7, even though the larger facility is only 6 2/3 times as large. They state that "a factor of seven is used based on the 10,000/1,500 ratio with additional space found in large-scale efficiency," apparently without realizing that using a larger factor implies that there are *dis*economies of scale.

[40] That is, we assume away the problem of "scaling" 5 fan units down to 3.5 fans, for example. Given the abundance of makers, brands, and capacities of industrial and agricultural production equipment, we do not expect this to be an issue.

[41] We could assign an opportunity cost to the usage of internally propagated plants, if they could be sold to other growers instead of used internally. However, we do not have the information needed to pursue this facet of costs. Regardless, since this would be one more cost factor that is proportional to output, it would only change the *level* of the average cost functions, without materially affecting its *shape*.

c) *Long run variable costs*

Certain costs are variable in the long run while fixed in the short run. These include rent, rental and security deposits, insurance, and certain forms of labor.[42] The figures for these are in Table V.2, and for the most part come from the Solstice report for what they term "fixed cost". The modifications we made were to assume that labor cost for management and janitorial work is proportional to facility size. The facilities Solstice examined in its report did not have these types of workers on payroll at the smaller facility, and so they did not impute a cost for them. Even if the smaller facilities do not actually have payroll expenses for janitorial or management work, there are still opportunity costs involved with the time devoted to these tasks, even if performed by an owner or other employee, and such costs should be included in an economic analysis. Therefore, we take the Solstice figures for management and janitorial labor at the 10,000 sf facility and linearly scale them for facilities of other sizes. While it may appear odd to assume that a 9,000 sf facility has "nine-tenths" the manager of the larger facility, we believe this is a good approximation reflecting that management may be shared between smaller facilities or how the manager's salary might change with the scale of his responsibilities. Similarly, assuming that janitorial work can be outsourced, it is reasonable to assume that contracts with firms providing janitorial services are roughly proportional to the work needed to be done, which in turn should depend directly on the size of the facility for the most part.

We assume that industrial space rents for $0.46/sf per month regardless of the size of the facility.[43] The range of operational scales we consider is relatively small within the context of the larger world of industrial and commercial real estate, and we did not find any indication that larger facilities should expect lower per-unit rental costs. The microeconomics of competitive capital markets implies that it makes no difference whether the operator of the facility owns or rents the building (from the long run economic perspective, that is), for if the building is owned then the rental rate becomes the opportunity cost of using the building instead of renting it to another user.

Assuming that in a standard rental contract the last month's rent must be prepaid and that a security deposit of size equal to a month's rent is required, then the contribution to economic cost of these two items is the opportunity cost of having that amount of money tied up, which is i per dollar per year.

The total of the long run variable costs works out to $14.62 per square foot of total size. This cost component is directly proportional to the scale of the operation.

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[42] While one may quibble whether any particular type of labor is a fixed or variable cost in the short run (and therefore whether we should discuss it here or in the next section), the advantage of the long run approach is that the distinction makes no difference. Both are variable costs in the long run.

[43] Our source is the "direct asking rents" for first quarter 2013 from Cushman & Wakefield (2013). For comparison, the Solstice report uses a figure of $0.50/sf/month.

d) Short run variable costs

Costs that vary with production quantity even in the short run include labor and non-labor inputs. We follow the Solstice report in separating labor for general farm work and trimming (also known as "manicuring"). These costs are shown in the bottom part of Table V.2. The other inputs in this category are electricity, water, soil, CO_2, nutrients, and pesticide. As discussed above in section A.1, we use the tariffs from Seattle Light & Power for the electricity rates. The tariffs, coupled with our assumptions on demand load and usage, lead to prices that are proportional to the scale of operations within each tariff. Since both the 1,500 and the 10,000 sf facilities are on the same tariff, the costs in the comparison columns of the table are proportional. However, electricity is relatively more expensive for smaller facilities. The other non-labor inputs are all directly proportional to scale.

Short run variable costs sum to $53.37 per square foot of total size for facilities larger than 1,350 sf. For facilities larger than 1,350 sf, this cost component is directly proportional to the scale of the operation. For facilities smaller than that, which must be on the less favorable electricity tariff, short run variable cost is $59.21 per square foot of total size.

e) Long run fixed cost

We found only two costs that are fixed in the long run. The first is the LCB license, as discussed above. The other is security monitoring, which the Solstice report costs at $45/month regardless of scale. Even together, these costs compose a very small portion of total cost, and thus create only mild economies of scale in production.

3. Assumptions and costs for the greenhouse production model

As discussed above, we lack cost information for greenhouse production with as much detail as we have for indoor production. In this section we describe how we estimate the cost of running a greenhouse operation of typical size for growing cannabis.

Instead of the bottom-up cost accounting we perform for indoor growing operations, our approach for greenhouse costs is different. We simply do not have the data to try to directly estimate economies of scale for greenhouse operations. We instead calculate a reasonable estimate for a greenhouse operation of size 32,670 sf. We then assume that there are mild economies of scale in growing cannabis in greenhouses, as in floriculture.

a) Production

While greenhouses may be operated in urban and suburban settings, we assume that efficient greenhouse operations will be undertaken in rural (or semi-rural) areas. Due to zoning restrictions, urban greenhouses may need to be glasshouses, which are much more expensive to construct than modern agricultural greenhouses composed of poly film, woven poly film, or polycarbonate sheeting over metal framing.

Therefore we envision the greenhouse production taking place on rented agricultural land. Each acre rented is assumed to be used 75% for the greenhouse itself, with the rest being used for paths and support areas. The scale of the greenhouse operation will always refer to the square footage of the greenhouse itself, although the full size of the parcel is used to calculate rental costs. For example, our one-acre typical setup encompasses a 32,670 sf greenhouse.

We assume that 65% of the space inside the greenhouse is used for canopy. This is at the low end of the 65-80% range we found in one source for general agricultural greenhouse production (WVUES, 2013) but slightly higher than the 60% assumed in Caulkins (2010). Thus the typical setup offers 19,602 sf of canopy. However, given the generally larger sizes of greenhouse and cheaper construction and rental costs per sf involved, we relaxed the assumption on the space required per plant. Instead of the 3′ by 3′ plot envisioned for each plant in the indoor scenario, we assume one plant per 16′ in the greenhouse scenario.

We assume there will be two harvests per year, in line with Caulkins (2010). A greater number of harvests per year could be achieved with more use of artificial light, but then the cost advantage of greenhouse growing begins to evaporate. Yields are assumed to be 35 grams per sf of canopy, the rounded figure from our indoor scenario, since greenhouse-specific cannabis production studies appear to be nearly nonexistent.[44] For comparison with other studies, we will also state the yields in various other metrics: 0.077 pounds per sf of canopy per harvest, 70 grams per sf of canopy per year, 45.5 grams per sf of greenhouse space per year, and 0.100 pounds per sf of greenhouse space per year.

b) Capital cost

Construction costs for greenhouses vary by type of construction, and a range of estimates is available in the literature. Caulkins (2010) mentions, without citing specific sources, a range of $5-12 per sf for construction cost for double walled polyethylene film greenhouses. WVUES (2013) cites construction cost that equate to about $13.30 in 2013 dollars (the actual costs cited are from 1990), but this includes equipment. About $8 of that amount is for the structure itself. At the risk of overestimating the cost for construction and equipment, we assume construction cost for the structure of $10/sf and an identical amount for equipment. Construction labor is subsumed into this cost, which is another reason we pick a number on the high end.[45] All costs for the typical greenhouse installation are in Table V.3. No building permit costs are included, since these structures are not for occupation.

[44] You might expect lower sf yields for greenhouse compared with indoor, since greenhouse grows would tend to have lower-intensity lighting.
[45] It is not always clear if construction estimates for greenhouse include labor cost, but at least some we examined do not.

For costs of genetic material, we borrowed from the Solstice figures for the indoor settings. The available growing space in the greenhouse on the 1-acre plot would allow about 1,225 plants to be grown in their 4' by 4' plots. With only two harvests per year and a greater dependence on the natural rhythm of the growing year, we did not assume that production was of the "perpetual harvest" variety. Therefore, no larger plants are needed at the beginning. We assume that plants in 1-quart pots will be purchased and planted, at a cost of $20 per pot. As with the indoor scenario, we assume all future plantings come from propagation onsite.

c) Long run variable costs

There is a wide range of land rental rates we could have chosen. From a USDA survey for 2012, we find that irrigated cropland rents for between $60/acre in the northeast area to $562 in Adams County (all figures in the survey are county averages, although some counties are aggregated with others).[46] We take rent for agricultural land to be $566/acre per month. This figure comes from Neibergs and Waters (2009), and pertains to land used for growing asparagus and potatoes in rotation in Franklin County, Washington. This figure may be high for our purposes, to the extent that prime cropland isn't needed for greenhouse operations so long as soil is purchased separately, as it is with indoor operations. We may thus be understating the cost advantages of greenhouse growing over indoor operations.

For insurance, in the absence of other information we assumed that the same cost per sf of indoor growing applies to the size of the greenhouse. If insurance rates in agricultural areas are lower in general, as we suspect due to lower rates of theft than in urban areas, then again we may be overstating the costs.

For management cost we relied on the outdoor farming estimate in the Solstice report, which assumed that a 10,000 sf outdoor growing area requires 60 management hours/month. Thus, assuming proportionality as for the indoor scenario above, our typical installation requires 196 hours of management per month.[47] We assume no janitorial labor is required.

Similar to the indoor scenario, we assume that two months' worth of rent will be tied up in prepaid final month's rent and a security deposit. As before, the only economic costs here are from the opportunity cost of having that amount of money invested in the greenhouse operation instead of elsewhere.

[46] Figures are from the Cash Rents Survey performed by the USDA National Agricultural Statistics Service. See http://www.nass.usda.gov/Surveys/Guide_to_NASS_Surveys/Cash_Rents_by_County/index.asp.

[47] As explained above, we don't take the proportionality literally; it is in part a stand-in for the higher salaries that management with more responsibility would be expected to earn.

The total of the long run variable costs works out to $4.20 per square foot of total size. This cost component is directly proportional to the scale of the operation.

d) Short run variable costs

For the price of electricity, we did not use the Seattle-specific tariffs used for the indoor scenario, because we envision that greenhouse production is likely to take place in less urban parts of the state. Accordingly, we examined the statewide all-inclusive price of electricity for Washington State for commercial and industrial users. In 2012, Washington State electricity providers had average revenue of $0.0767/kWh for commercial customers and $0.0411 for industrial customers.[48] While cannabis growers would be considered industrial customers, we hesitate to adopt the lower figure. From our examination of electricity tariffs offered by various utilities around Washington State, it is clear that the largest industrial customers get significant discounts on their rates. However, cannabis producers will be nowhere near the demand loads necessary to procure electricity at the most-favorable rates. To avoid having this one assumption create a possibly artificial difference in cost between indoor and greenhouse growing, we took the average price per kWh from the indoor scenario (from the lower priced tariff): $0.0596.

For electricity usage, we assumed that, subject to an arbitrary scaling factor α, the electricity needs of a sf of greenhouse are the same as those for a sf of production space in the indoor scenario. We chose α to be 25%, inside the range of 0 to 33% conjectured by Caulkins (2010). For the other short run variable inputs apart from labor (soil, CO_2, nutrients, pesticide), we generally assumed that the requirements per sf of canopy were the same as for the indoor scenario, with an adjustment made for the different footprints of the plants (9 sf in the indoor scenario versus 16 sf in the greenhouse scenario). The exception was for soil, for which we did not adjust for the different footprint of a plant. These are the other short-run variable costs are in Table V.3.

For general farm labor, we began with the figure from the 14,000 sf indoor source data in the Solstice report and scaled it according to the size of the greenhouse, subject to an arbitrary scaling factor β. Following the lead of Caulkins (2010), we set β = 50%. This resulting amount of labor is also consistent with the Solstice report's figures for their outdoor growing scenario, after adjusting for the differing number of crops in the outdoor grow. Trimming labor was taken to be proportional to production at the same rate of 41.43 grams per hour as used above.

e) The cost function

As mentioned in section IV.C, we made use of these authors' estimated cost elasticity by taking the midpoint between their estimates of mild economies of scale and no economies of scale. We thus assume that cost elasticity is 0.913 for greenhouse growing of cannabis. We use this

[48] US Dept. of Energy, Energy Information Administration, Electricity Data Browser (http://www.eia.gov/electricity/data/browser/).

figure to calibrate a cost function that matches our two assumptions: 1) cost at size 32,670, excluding the LCB license (which has no counterpart in the floriculture industry upon which estimation Schumacher and Marsh' (2003) estimate is based) is as found from the calculations above, and 2) elasticity is 0.913 everywhere across the range of scales we consider. We thus assume that the cost function can be well approximated by an isoelastic cost function passing through the quantity and cost estimated for our typical greenhouse. We then add the LCB license fee and cost of security monitoring on top of the estimated cost curve.

The cost function (i.e., all cost except the LCB license) can be approximated by a simple power function, and is of form

$$C(Q) = aQ^b$$

where Q is quantity (here taken to be greenhouse space—since by assumption we take actual production quantity to be proportional to greenhouse space, this choice is immaterial for purposes of calibrating the cost function) and (a,b) is a pair of unknown parameters. Assume that cost is known to be C_0 at Q_0 and that elasticity is known to be ε_0 at Q_0. The two assumptions give rise to a pair of equations that we can solve for the two unknowns a and b. The first equation, $C(Q_0) = C_0$, implies:

$$C_0 = aQ_0^b$$

Economists calculate cost elasticity as:

$$\varepsilon(Q) = C'(Q)\frac{Q}{C(Q)}$$

Where the first term on the right hand side is the derivative of the cost function. So the second equation for the elasticity at Q_0 is:

$$\varepsilon_0 = b$$

That is, for our chosen form for the cost function (known as an *isoelastic* function), elasticity is constant, which makes it particularly convenient for our calculations. Plugging in elasticity for b into the first equation above and solving for a yields:

$$a = C_0 {Q_0}^{-\varepsilon_0}$$

To calculate the total long run variable cost for any other quantity, Q, the following formula is used:

$$C(Q) = C_0 Q_0^{-\varepsilon_0} Q^{\varepsilon_0} = C_0 \left(\frac{Q}{Q_0}\right)^{\varepsilon_0}$$

Plugging our elasticity estimate and Q_0 = 32,670 (our typical size greenhouse) into this last equation yields this annual cost equation (where we have also added in the license and security monitoring cost):

$$C(Q) = 1000 + C_0 \left(\frac{Q}{32670}\right)^{-0.91335}$$

Given any particular value of C_0, which varies with the horizon of the scenario, the long run average cost function (LRAC) can then be calculated by dividing $C(Q)$ by quantity.

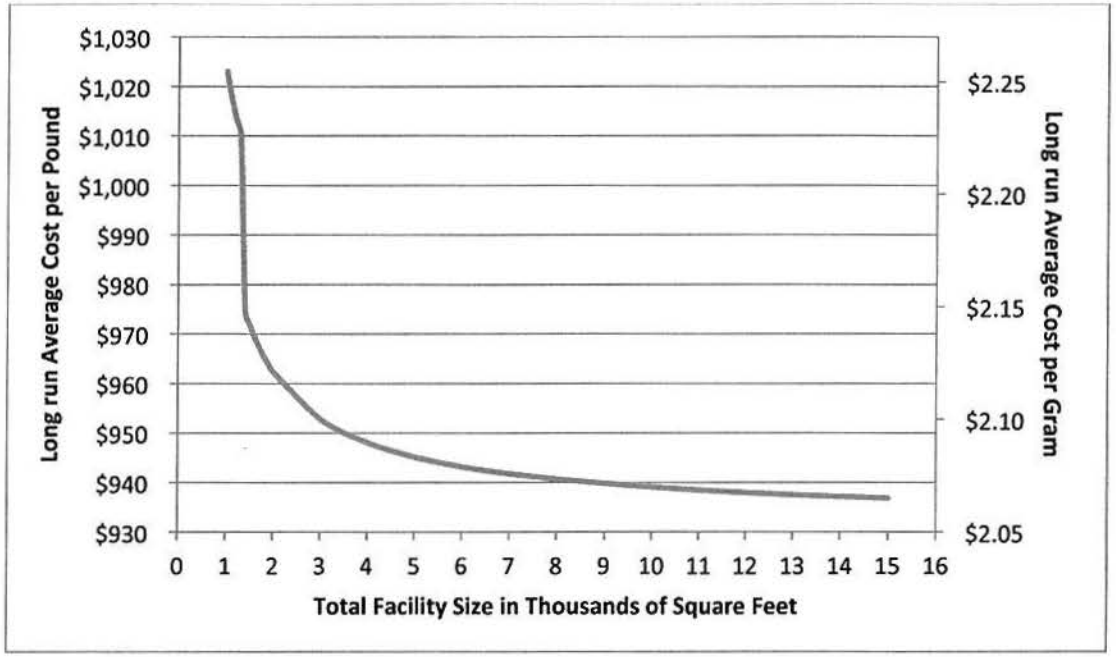
VI. Estimated cost function

With the assumptions and calculations of the previous section now in hand, we can present our estimated cost functions for growing cannabis. For each type of growing we present the cost curves for several time horizons. Economies of scale are exhibited when average cost functions are decreasing with quantity (or facility size, in our application). There the shape of the LRAC functions we present are of particular interest.

A. Cost functions for indoor growing

The LRAC functions we compute are depicted in Figure 2 and Figure 3 for indoor growing of cannabis. The horizontal axis is the total size of the facility, including non-production space. We calculated LRAC for indoor facilities ranging from 1,000 to 15,000 sf. We could just as well have plotted the LRAC curves against production space or sf of canopy, but that would only change the horizontal scale without affecting the shape of the curve. The left vertical axis measures annualized LRAC per pound of production, and the right axis measures the same in grams.

Figure 2: Indoor LRAC Curve, One-Year Scenario



The LRAC function for indoor growing of cannabis with a one-year horizon is in Figure 2. With such a short horizon, average costs are the largest among all the scenarios we consider, because there is so little time over which to amortize the sunk costs of capital and equipment. LRAC ranges from a high of $1,023/pound ($2.26/gram) per annum for the smallest (1,000 sf) facility to a low of $937/pound ($2.07/gram) for the largest (15,000 sf) facility. LRAC is decreasing everywhere, implying that overall, there are mild economies of scale. Taking discrete change from a 1,000 sf facility to a 15,000 sf facility, the implied elasticity of cost with respect to quantity[49] is 0.910, strikingly close to the figure of 0.913 that we assume without such detailed information for the greenhouse scenario.[50]

[49] The formula for the cost elasticity from a discrete change in quantity is %Δ (Total Cost)/%ΔQuantity.

[50] We did not choose our greenhouse cost elasticity estimate to make it conform to this result; we settled on the midpoint formula for the assumed cost elasticity before we made this calculation.

The most striking feature of the cost curve is the large decline in average cost once the threshold of 1,350 sf is passed and the enterprise can take advantage of the more favorable electricity tariff. Beyond that size threshold, further economies of scale come from the other cost aspects discussed above (most notably, the long run fixed costs, the permitting, and certain construction items as detailed in section V.B.2).

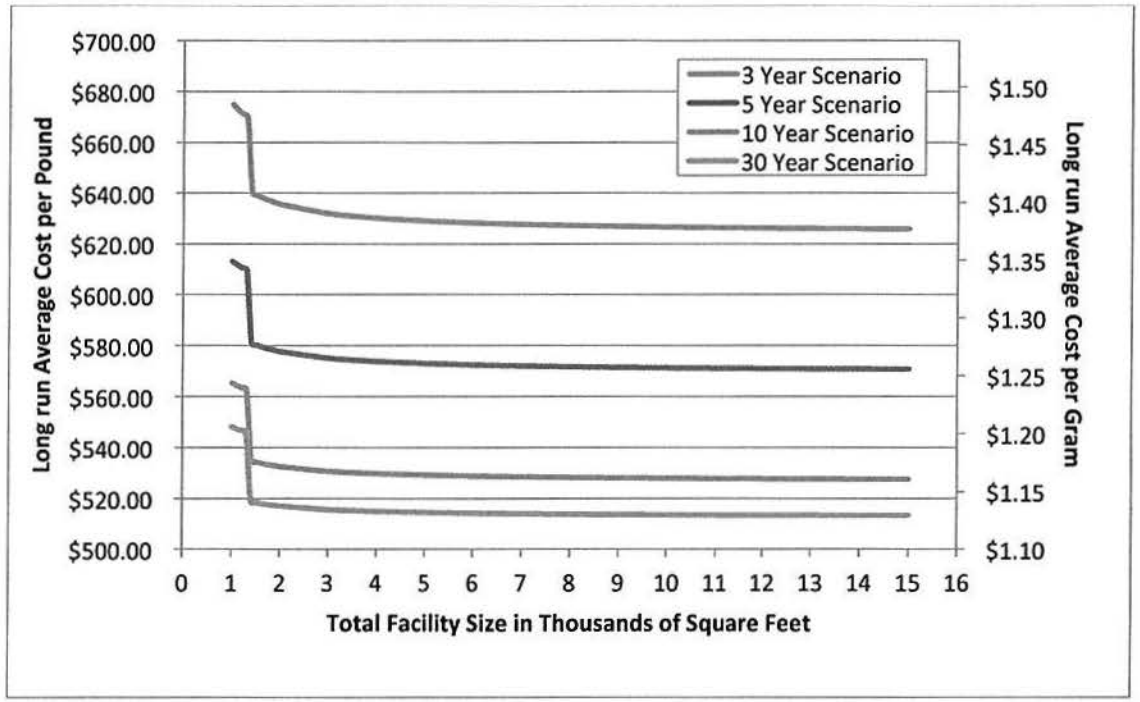
The LRAC curves for the three, five, 10, and 30-year scenarios are in Figure 3. Each has basically the same shape as the shorter horizon scenario, but of course the level of average cost for any quantity decreases as the horizon increases, up to the least common multiple of the various capital and equipment lives (30 years).

The horizon chosen makes quite a difference in the level of cost. For example, a 1,500 sf facility has annualized average cost per pound of $972 with a one-year horizon, $639 with a three-year horizon, $580 with a five-year horizon, $534 with a ten-year horizon, and $518 with a 30-year horizon. These declines in cost with the longer horizons are far greater than the cost decreases stemming from economies of scale within any one horizon.

The final curve in the figure, for the 30-year scenario, represents minimized LRAC.[51] At the larger facility sizes, costs converge to about $513 per pound ($1.13/gram). The level of the 30-year LRAC curve is about 54% that of the one-year scenario. Our analysis thus reveals one reason why prices so high in the cannabis industry. Expected LRAC is the average of the LRAC curves, where the weights in the averaging are the probabilities that each scenario is the relevant one. When enforcement risk is large, there is a greater chance of ending up with one of the shorter horizons, and that leads to higher costs (and therefore prices). And this consideration applies even before marking up costs even further to account for risk aversion.

[51] Extending the horizon beyond 30 years increases LRAC (unless the horizon is a multiple of 30), because any other horizon leaves some capital unused (i.e., not fully physically depreciated) at the terminal period.

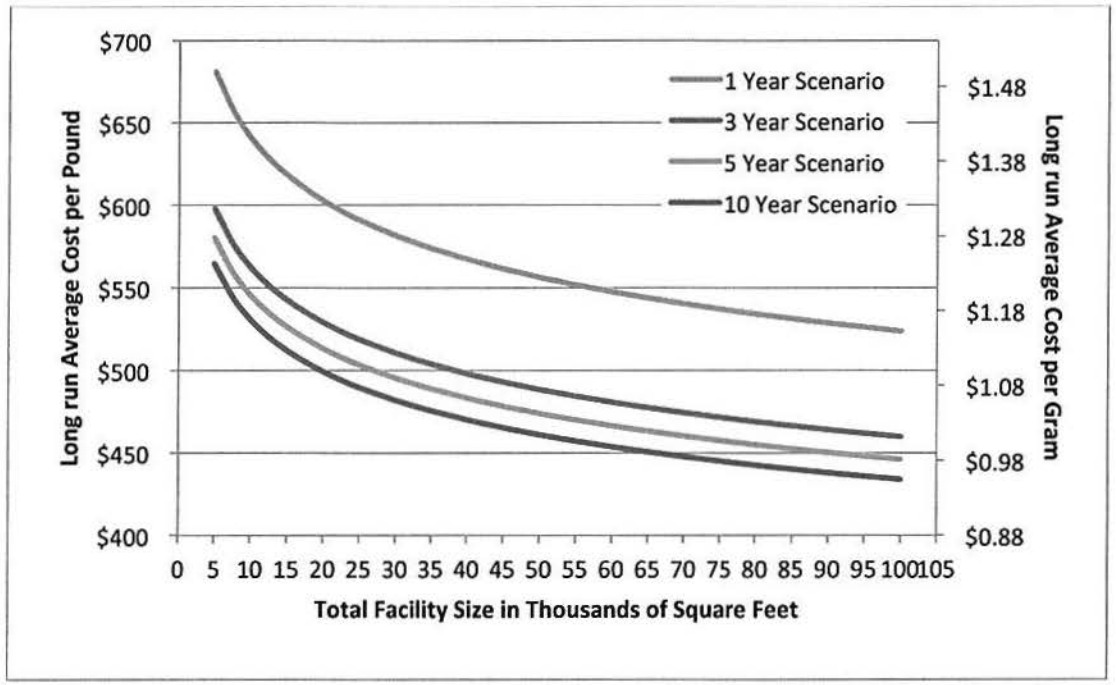
Figure 3: Indoor LRAC Curves, Three- to 30-Year Scenarios



B. Cost functions for greenhouse growing

The LRAC functions for growing cannabis in greenhouses are all in Figure 4. Here we consider a scale range from 5,000 to 100,000 sf. Except for the smallest greenhouses in the longer horizons, where our approximation error involved in the isoelastic cost function estimation is greatest, production costs are lower than for the indoor scenario, as expected. Our assumption that cost is isoelastic ensures that each curve has a "textbook smooth" shape. In the one-year scenario, annualized LRAC ranges from $681 to $584 per pound. In the 10 year scenario, which is the minimum long run cost horizon for this case, annualized LRAC ranges from $565 to $434.

Figure 4: Greenhouse LRAC Curves, One- to 10-Year Scenarios



C. Comparison of cost functions for indoor and greenhouse growing

To facilitate comparison of indoor and greenhouse growing, Figure 5 shows the LRAC curves for indoor and greenhouse production in the one-year horizon, and shows that greenhouse growing enjoys a significant cost advantage.

Figure 6 shows that in the five-year horizon, the relative advantage of greenhouse growing is not as large as in the one-year scenario. It is the greater capital costs of indoor construction that create a large part of the cost disadvantage of indoor growing, and that factor shows up the more acutely the shorter the horizon (differences in energy costs are an important part of the remaining difference.

Figure 7, we plot the cost curves already presented together on the same graph

Figure 5: Indoor vs. Greenhouse LRAC Curves, One-Year Scenario

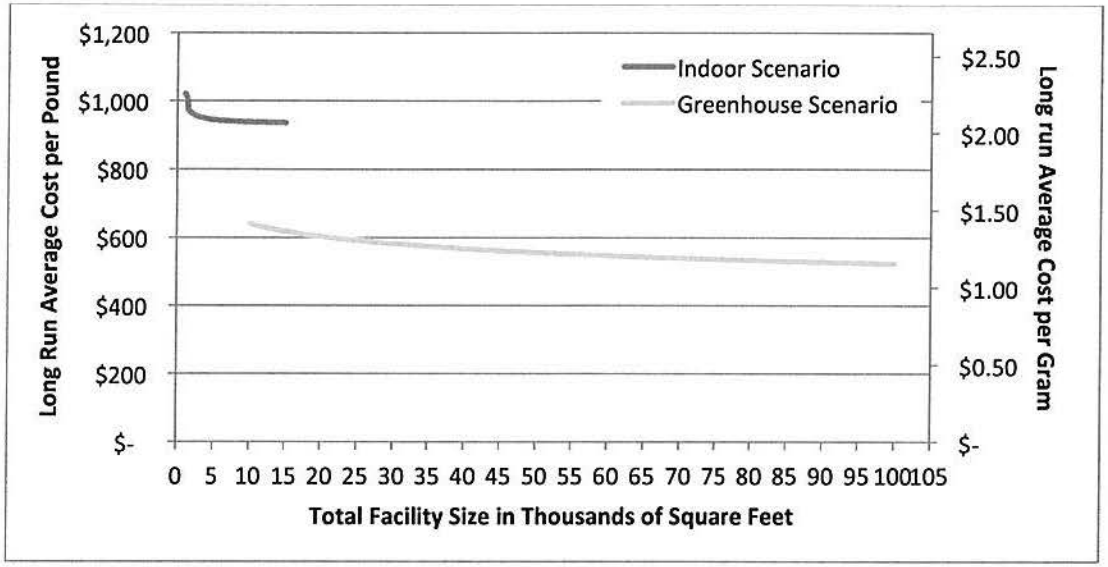


Figure 6: Indoor vs. Greenhouse LRAC Curves, Five-Year Scenario

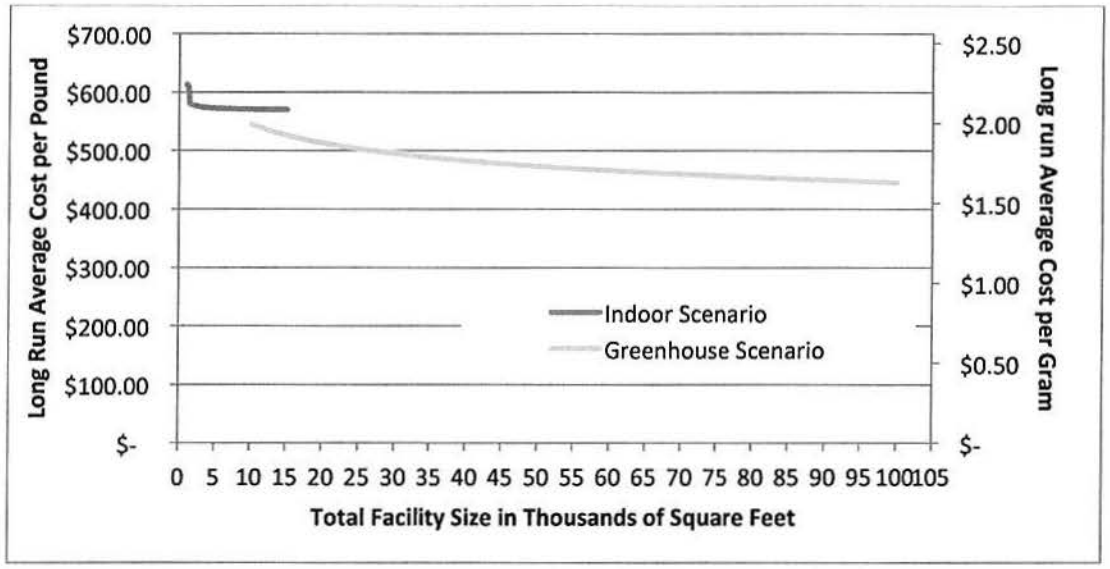
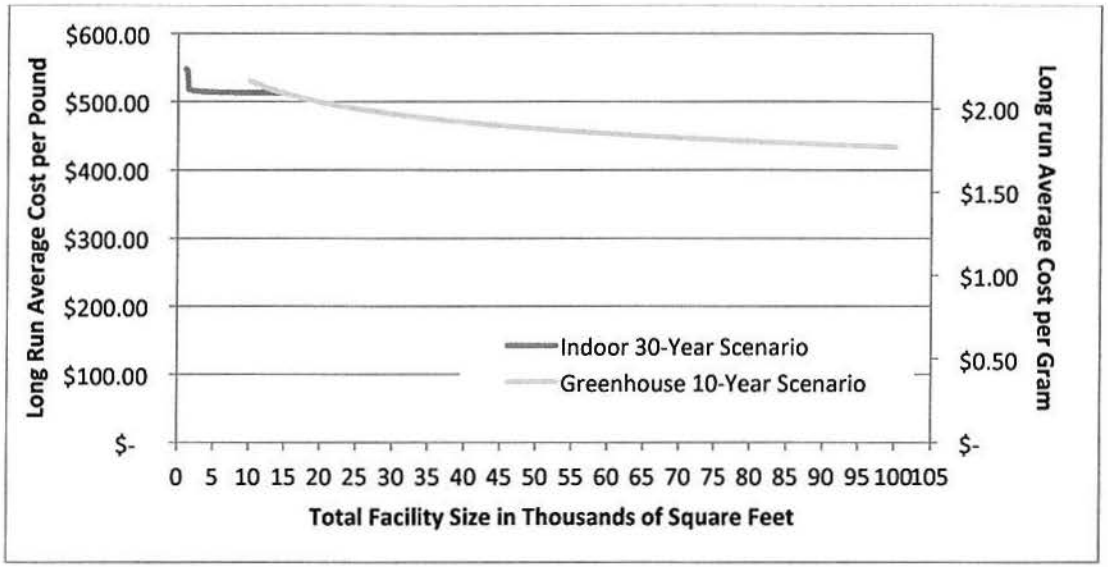


Figure 7: Indoor vs. Greenhouse LRAC Curves, Minimum-Cost Scenario



VII. Implications for the LCB

Our estimates suggest that the economies of scale for the indoor production of marijuana are modest. The economies of scale for greenhouse growing are larger than for indoor growing, but even these are relatively mild. This conclusion was reinforced in the perspectives we solicited from growers responding to our cost-of-production survey. The growers surveyed were of the opinion that there would be some unit cost advantages to increasing the size of their operations (in particular they referenced quantity discounts on inputs), but that the gains would not be substantial. Only one-third of the respondents were of the opinion that they would enjoy substantial reductions in costs if they were to substantially increase the scale of their operations.

These estimates provide only a limited understanding of likely economies of scale in response to legalization of commercial production, as they focus on technologies currently available and cover only a limited span of sizes of growing operations. Our interviews with large growers lead us to conclude that the economies of scale for large outdoors grows (multi-million dollar operations) might be substantial and would follow largely from the professionalization of the production processes. While cost reductions in the 1,000 to 50,000 square feet range might be

modest, a price drop anticipated for larger producers might be substantial. Legalization will likely lead to significant innovation in marijuana growing technology as the newly legalized market seeks new ways to lower costs and increase profitability. The technological revolution and improvements in professional production management following legalization will disproportionately benefit larger-scale producers as only larger outfits would be able to invest in the technology and expertise needed for professional process management. As operations professionalize, security costs (which were factored in here at only $45 per month, regardless of scale) would likely increase. As the size of the operations increase, and as more-expensive technology is deployed, the security risks might be higher, entailing greater security monitoring costs. On the other hand, we are also more likely to see security services tailored to cannabis production made available, and active competition in the provision of such services may keep costs moderate. Nevertheless, as this security market develops we might see an increase in spending on security.

Many existing growers in Washington State face barriers to significantly expanding their operations. Our survey of growers reveals a surprisingly high cost of money. Our respondents reported an average effective annual interest rate of 32%, which reflects a significant risk premium. Many of the growers we interviewed regarded access to formal banking services to be a major setback to their efforts to expand operations. A further barrier is the ongoing risk of federal enforcement (which is reflected in the interest risk premium). Given that the costs of expanding operations are heavily front-loaded, a longer production time horizon affords growers a longer period to amortize costs and recoup their upfront investment. Attitudes regarding the benefits of expanding operations are strongly influenced by growers' perceptions regarding the likelihood of the federal government seizing their assets.

Our economies of scale analysis is limited to indoor and greenhouse grows (when we produced our estimates WLCB was not considering allowing outdoor growing). As outdoor growing is now a live possibility, an important next step is to develop cost estimates specific to outdoor growing. This would require interviews targeting outdoor growers (of various sizes). A detailed analysis of costs of existing outdoor growers should be supplemented with the econometric literature on nearest-neighbor crops, to provide some perspective on how costs might change for a mature industry where technological innovations have been realized.

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Tables

Table V.1: Indoor Cannabis Production: Capital Cost

			1,500 sf Facility		10,000 sf Facility	
	Wage	Markup	Hours	Initial Value of Capital	Hours	Initial Value of Capital
Construction						
Labor						
Design	$27.64	200%	12.00	$663	80.00	$4,422
General contracting	$53.77	200%	77.65	$8,350	517.65	$55,668
Electrician	$29.59	200%	70.00	$4,143	150.00	$8,877
Plumber	$28.71	200%	60.00	$3,445	400.00	$22,968
Skilled carpenter	$23.32	200%	50.00	$2,332	350.00	$16,324
HVAC professional	$25.74	200%	50.00	$2,574	80.00	$4,118
Security system installer	$23.14	200%	5.00	$231	40.00	$1,851
Permitting				$823		$2,672
Subtotal construction				*$22,562*		$116,901
Equipment						
Cultivation				$12,741		$84,939
Environmental				$26,214		$174,760
Lighting				$32,935		$219,567
Nutrient delivery				$2,611		$17,405
Finishing				$942		$6,281
Subtotal equipment				*$75,443*		$502,952
Genetic Stock						
Plants and rooted clones				$4,500		$30,000
Total Initial Value of Capital				$102,505		$649,853
Startup cost per sf				$68.34		$64.99

Table V.2: Indoor Cannabis Production: Long Run and Short Run Variable Costs, per annum

			1,500 sf Facility		10,000 sf Facility	
	Wage	Markup	Hours	Economic Cost	Hours	Economic Cost
Long Run Variable Costs						
Labor						
Management	$41.79	130%	223	$12,107	1,486	$80,714
Janitorial	$13.12	130%	54	$914	357	$6,091
Rent-related Cost						
Rent				$8,280		$55,200
Last month rent + security deposit (opportunity cost)				$138		$920
Insurance				$494		$3,456
Subtotal LRVC				$21,933		$146,382
LRVC per sf				$14.62		$14.64
Short Run Variable Costs						
Labor						
General agricultural worker	$10.60	130%	223		1,486	$20,473
Trimming	$10.60	130%	2,360	$32,521	15,733	$216,805
Non-labor inputs						
Electricity				$28,553		$190,355
Water				$480		$3,200
Soil				$8,303		$55,353
CO_2				$2,631		$17,540
Nutrients				$5,090		$33,933
Pesticide				$2,400		$16,000
Subtotal SRVC				$83,049		$553,660
SRVC per sf				$55.37		$55.37

Notes: Trimming wage bill is for years after the first. First year trimming wage bill is only 5/6 as much, since there is no harvest in first two months.

Table V.3: Greenhouse Cannabis Production: Costs for a Typical Operation

		34,640 sf Facility
Capital Costs	Assumption	*Total Cost*
Construction	$10/sf of greenhouse space	$326,700
Equipment	$10/sf of greenhouse space	$326,700
Genetic stock	0.0635 plants/sf of growing space	$24,503
Total initial value of capital		$677,903
Startup cost per sf		$20.75
Long Run Variable Costs		*Cost Per Annum*
Management Labor	196 hours/month; same wage and markup as for indoor scenario	$127,790
Rent-related Cost		
Rent	$566/month	$6,792
Last month rent + security deposit (opportunity cost)	Security deposit is equal to one month's rent	$113
Insurance	$0.33/sf of greenhouse space p.a.	$10,781
Subtotal LRVC		$145,476
LRVC per sf		$4.20

Short Run Variable Costs		
Labor		
General agricultural worker	202 hr/month; same wage and markup as for indoor scenario	$33,443
Trimming	Trim rate = 41.42 g/hr; same wage and markup as for indoor scenario	$456,386
Non-labor inputs		
Electricity	Needs 25% as much as indoor; price = $0.0596/kWh	$222,108
Soil	Same amount needed/sf canopy as indoors	$221,436
Water	9/16 × same amount needed per sf canopy as indoors	$12,801
CO_2	"	$70,167
Nutrients	"	$135,747
Pesticide	"	$64,007
Subtotal SRVC		$1,216,095
SRVC per sf		$35.11
Long Run Fixed Costs		
LCB license	$1000 p.a. renewable	$1,000
Security monitoring	Same as for indoor scenario	$540

WORKING
PAPER

Estimated Cost of Production for Legalized Cannabis

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Estimated Cost of Production for Legalized Cannabis

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Abstract
This paper tries to estimate post-legalization production costs for indoor and outdoor cannabis cultivation as well as parallel estimates for processing costs. Commercial production for general use is not legal anywhere. Hence, this is an exercise in inference based on imperfect analogs supplemented by spare and unsatisfactory data of uncertain provenance. While some parameters are well grounded, many come from the gray literature and/or conversations with others making similar estimates, marijuana growers, and farmers of conventional goods. Hence, this exercise should be taken with more than a few grains of salt. Nevertheless, to the extent that the results are even approximately correct, they suggest that wholesale prices after legalization could be dramatically lower than they are today, quite possibly a full order of magnitude lower than are current prices.

1. INTRODUCTION

This paper tries to estimate post-legalization production costs for indoor and outdoor cannabis cultivation as well as parallel estimates for processing costs. A byproduct of this analysis is some insight into the scale of utilization of various factor inputs.

Commercial marijuana production and processing for general or recreational use is not legal anywhere, not even (as is often incorrectly asserted) in the Netherlands. Hence, this is an exercise in inference based on imperfect analogs supplemented by spare and unsatisfactory data of uncertain provenance. Broadly speaking there are two kinds of analogies: Illegal cannabis production and legal production of agricultural products that might for various reasons be seen as similar to cannabis. Neither presents a sound foundation for extrapolation, and the extrapolation is fraught with conjecture and reliance on grey literature rather than the scientific literature. While some parameters are grounded in standard academic literature or government agency estimates, many come

from the gray literature[1] and/or conversations with others making similar estimates, marijuana growers, and farmers of conventional goods. The reader is cautioned that this exercise, while a good faith attempt, should be taken with more than a few grains of salt.

A particular concern is uncertainty about potential process innovation and automation engendered by larger operating scales and freer information flow. We generally assume that competition will drive productive efficiency toward to the top of the range of practices seen currently, but do not consider the possibility of fundamental innovation.

Nevertheless, to the extent that the results are even approximately correct, two primary conclusions are that: (1) Even production costs of marijuana when it is illegal do not seem large enough to account for current price levels[2] and (2) Production costs after legalization could be dramatically lower than they are today, quite possibly a full order of magnitude lower than are current prices.

2. COSTS OF INDOOR ILLEGAL CANNABIS PRODUCTION

We attempt to estimate production costs for three modalities: (1) private, non-commercial 5' x 5' indoor hydroponic grow with lights, (2) devoting an entire 1500 square foot residential house to indoor growing with lights as a commercial operation, and (3) greenhouse-based commercial growing. The distinction between the second and third comes primarily from different electricity, land, and structure costs, and also the number of harvests per year.

2.1: Materials and Consumables

The grey literature is rich with very detailed explanations of how to grow marijuana, and price quotes for the equipment and materials are readily available online, so it is possible to estimate the costs of materials and consumables.

A Carnegie Mellon Heinz student under our supervision generated a cost estimate for a hypothetical hydroponic set-up in a 5' x 5' space that is allowed under section 3.ii of The Regulate, Control, and Tax Cannabis Act of 2010.[3] He concluded the consumables (growing medium and nutrients) totaled on the order of $300 per harvest. Electricity at 40

[1] We cite primarily Cervantes (2006) and Edwards (2006) since they are readily accessible books. We endeavored to cross check statements in those books with various web sites and blogs. Still, mere repetition of a statement in multiple non-refereed sources is no guarantee of accuracy (cf., Reuter, 1984); at best it means we are capturing some nebulous community's conventional wisdom, but not necessarily objective facts.

[2] Indeed, there are already media reports of declining wholesale prices (e.g.,), although official price series are more stable.

[3] Thanks to Josh Swiss for this analysis.

watts per square foot and $0.14 per kwH added another $200 per harvest.[4] Durable items (fan, lights, air stone, pump, tubing, sheers, etc., apart from light bulbs) totaled $1,250 - $1,500, but if they could be amortized over four harvests per year for five years shrank to $60 - $75 per harvest.[5] Interesting, light bulbs (with an assumed life time of one year) were a non-trivial cost item, at $27.50 per harvest. Altogether, the student estimated costs per harvest in the vicinity of $600.

Yield estimates are grounded in Toonen et al.'s (2006) study of 77 illegal, indoor growing operations in the Netherlands. They found a median planting density of 15 plants per square meter, or 1.4 plants per square foot, and an average yield of 1.2 ounces of saleable material per plant per harvest.[6] That translates to 0.105 pounds per square foot per harvest or 2.625 pounds per 25 square feet per harvest. Combining this with the $600 figure derived above, the materials and consumables cost per pound is about $225 per pound.

That is, a well-run 5' x 5' hydroponic grow producing 4 harvests per year might yield 10.5 pounds per year with tangible costs of $225 per pound--$75 per pound for electricity and the remaining $150 per pound for other factors.

These costs work out to be quite consistent with those described in a Dutch case study described by Cervantes (2006, p.148). That case study described three harvests: (1) a modest 8.4 pounds grown on 128.6 square feet at a cost of $5,647, (2) a subsequent investment of $8,220 that doubled the area cultivated and improved methods, yielding 27.6 pounds, and (2) a third harvest in the full space of 30.2 pounds whose incremental cost was only $1,882. That works out to ($5,647 + $8,220 + $1,882) / (8.4 + 27.6 + 30.2) = $238 per pound.

Of course the costs per pound in Cervantes' case study decline if the first two harvests are effectively investments to get the operation running. The cost per pound during the third harvest was only $62 per pound, lower even than just the cost of electricity estimated for

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[4] This assumes 24-hour light for the first 30 days and 12-hours of light for the remaining 60 days. That's 1,440 hours of light per harvest. 40 watts per square foot (mid-range from Edwards, 2006) times 25 square feet conveniently gives 1 kwH per hour of lighting. Electricity prices from US Energy Information Administration (2009).

[5] Amortizing equipment costs at 20% per year is a common practice in budgeting greenhouse operations for legal crops (e.g., Ohio State University Extension, 2008), but it has not specific empirical basis with respect to marijuana growing equipment in particular; it is a good example of a parameter grounded in judgment not data. Assuming four harvests per year is typical of indoor operations, allowing 30 days in the clone/vegetative and 60 days in the flowering stage.

[6] One source of confusion in the literature is whether yields are quoted per square foot of flowering plants or per square foot of total growing area (including area for clones and plants in the vegetative state). We presume Toonen et al.'s yields pertain to all area with plants, but there are four harvests per year. Some estimates are based only on the part of the grow area with flowering plants, but then assume six harvests per year since the plants only spend 60 not 90 days in that area.

the 5' x 5' grow. The longer the operational life over which the initial investment could be amortized, the lower the total cost, but within two years of four harvests per year (i.e., the three harvests described by Cervantes plus a hypothetical five additional harvests like the third), the cost could be $116 per pound.

There are at least three reasons why Cervantes' case study costs were lower per pound: (1) Some materials might be purchased at lower unit costs when operating at such a largest scale (258.5 square feet vs. 25 square feet), (2) the case study took place in the Netherlands, where there is a good infrastructure for supporting such activities, and (3) Cervantes' book is a how-to guide for marijuana growing and how-to guides may have an incentive to offer a favorable, not a representative case study. The third is a particular concern; we speculate that Cervantes case study may not be representative of average grow costs today, being something of a best case. Indeed, Cervantes describes the great importance of the two growers being able to tap the expertise of someone with considerable experience. However, after legalization when it becomes easier for such consultants to advertise their services and fewer people are trying to work their way up the learning curve with limited assistance beyond internet web sites, a favorable outcome in today's term may become the norm.

For the sake of particular numbers, for indoor, lighted growing we will carry forward the electricity costs from the 5' x 5' grow (at $75, based on 40 watts per square foot), but consider a range of other costs from $50 - $150 per pound.

Electricity costs for greenhouse growing could be essentially zero if only natural light is used, but might still exist at some level if artificial lighting is used to control the flowering cycle. We will arbitrarily assume the upper end of that range is one-third of the cost of an indoor grow with purely artificial light.[7]

2.2: Labor

The grey literature is rich with very detailed explanations of how to grow marijuana, but generally does not provide precise estimates of labor requirements. This is not surprising. At present marijuana cultivation is a cottage industry, and labor hours per pound produced appear to vary enormously depending on : (1) skill level; novices take longer and produce less per plant or per unit area than do average growers, let alone the most skillful; (2) individual traits; two people at the same point on a learning curve may still have different productivity rates in the same way that some people consistently manage better yields than others from home garden plots; and (3) operational scale; marijuana cultivation involves many steps and amortizing the fixed or "set up" costs of those steps over a larger production volume greatly reduces the labor input per pound produced.

[7] This upper end guess is an obvious candidate for improvement in a refined analysis.

There are plausible arguments why legalization could positively affect labor productivity in all three respects. If marijuana production were legal and normalized, most workers would spend most of their careers further up the learning curve both because more would be full time workers, not hobbyists, and because companies in the business would be able to establish training programs for new hires. Likewise if marijuana production were just another industry, workers would sort into that industry based on affinity and natural ability. At present, the dominant selection filter determining who works as a marijuana grower is willingness to participate in illegal drug production, and there is no reason to think that subset of the population is the subset with the greatest skill at horticulture. Finally and most obviously, legalization would presumably allow economies of scale and better information exchange. E.g., it would be even easier for consultants to sell their expertise in productivity enhancing tricks of the trade than it is at present.

The extent to which these efficiency gains are realized may well depend importantly on how aggressively federal law enforcement officials investigate and prosecute marijuana producers. If federal enforcement agencies took a hands-off approach, then marijuana production in California could enjoy the efficiency gains characteristic of most industries in a competitive free market. At the other extreme, sufficiently aggressive federal enforcement might force production to remain dispersed and discrete, as it is today.

To be conservative, in our estimates of legalization's potential effects on production costs we will base our conjectures about labor productivity on the high-end of what can be achieved today, rather than factoring in hypothetical subsequent efficiency gains. Note: What we discuss in this section is just the labor effort involved in growing the marijuana; harvesting and processing stages are discussed in a different section, later in this paper.

However, we do presume that the labor wages would decline. That is, we imagine that even if federal law enforcement were to break up flagrant producers, it would seek to prosecute only the proprietors, not the laborers. So we imagine that industry wages would fall to the levels of other agricultural workers.

For present purposes we do not need to know what the current hourly wage rates are, but we did run across a number of statements in the grey literature suggesting that $20 to $25 per hour might not be atypical of cash payments.[8] By way of contrast, agricultural workers in California harvesting and tending legal crops typically cost the employer no more than $10, including whatever benefits are (or are not) provided. For example, O*NET (2010) cites an average wage for California nursery and greenhouse laborers of $8.60/hour.

[8] Often some of the compensation is in-kind or the labor is provided by someone with an ownership stake in the marijuana being processed. The $20 - $25 figure is meant to reflect instances in which the compensation arrangements reflected a straight wage.

Labor Cost for a Private 5' x 5' Hydroponic Grow

Perhaps the best way to think about the labor required for a private, non-commercial 5' x 5' grow is that it is akin to a serious hobby, probably not more than an hour a day once the set-up had been created. In many cases the labor would be provided by the person who owns (or rents) the physical space and the marijuana plants; that "proprietor" would not literally pay himself or herself in cash for the time.

Economists rightly note that there is an opportunity cost to uncompensated time. So a formal analysis might suggest imputing a charge equal to the average wage in the growers' legitimate, day job. However, that strikes us as not the best way to think about it given that growing plants is an enjoyable activity for a not small subset of the population.

We previously estimated that a well-managed 5' x 5' hydroponic grow can produce about 10.5 pounds of marijuana per year. A number of studies suggest that the average quantity of marijuana consumed per past-year user is close to 100 grams (Bouchard, 2008; Kilmer & Pacula, 2009, UNODC, 2009). So a single 5' x 5' home grow could provide enough marijuana for about 50 average marijuana users.[9] We would guess that at least one in 50 people generally and, hence, likely one in 50 marijuana users would enjoy gardening enough to find growing to be pleasurable, both in its own right and for the associated social pleasures of trading gossip about the process with other growers.[10] Hence, it does not make sense to cost this time as if it were work.

This is not to deny that skill and effort are required to grow marijuana (especially high quality marijuana); we are merely arguing that even if it were possible to estimate average hours involved and average wages of those who would have private grows, such a quantification would not improve the accuracy of the cost-estimate because it would overlook intangibles that are plausibly of the same order of magnitude.

Instead, we prefer to think of the production cost of home-grown, non-commercial marijuana as including both a tangible dollar cost and a non-commensurable additional in-kind donation of hobbyists' time (and space, as is discussed below).

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[9] 10.5 pounds * 453.6 grams per pound / 100 grams per person = 47.6. One could refine this calculation. The actual average is just shy of 100 grams, and the 10.5 pounds would likely all be sinsemilla, whereas the ~100 gram average is based on some mix of grades, including some lower quality. On the other hand, grams consumed per person per year might be higher after legalization. For the purposes of this present argument, greater precision would not change the basic argument.

[10] We stress the word "guess". We found no formal survey or estimate, but home gardening of legal plants (vegetables, flowers, etc.) is common enough to support multiple magazines, a cable television network, gardening clubs, and garden supply companies. The National Garden Association claims that 83% of American households participated in some sort of do-it-yourself indoor or outdoor lawn and gardening activity (http://assoc.garden.org/press/press.php?q=show&id=2617&pr=pr_nga), but that is a much broader definition than what is relevant here, which would be serious indoor gardening enthusiasts.

Labor Cost for a Commercial Growing Operation in a House
This section focuses on commercial indoor growing in houses. If marijuana were fully legal in all respects, including with respect to federal law, there would be no reason to grow marijuana in residential houses. Greenhouses are cheaper to build and maintain and take better advantage of natural light. However, one possible stance of federal law enforcement would be to enforcement federal marijuana laws against brazen growing on farms (in fields or greenhouses), but to ignore covert operation.

We will assume that a single, full-time person could manage a 1500 square foot house growing 1300 square feet worth of marijuana. (The 200 square foot difference allowing for walkways and other non-grow areas.) There are several reasons to think this is plausible. First, small groups of organized growers have been known to carry out such operations in multiple houses at once (Bouchard and Nguyen, forthcoming). Second, Cervantes (2006) case study involves two people with full time jobs cultivating approximately 260 square feet worth of marijuana without describing it as unduly burdensome outside of harvest time, and, as noted, harvest and processing labor is dealt with separately below. Third, it seems generally plausible based on the grey literature's descriptions of cultivation processes, although admittedly the grey literature tends not to quantify labor effort per step.

A typical productivity rate for intensive indoor growing is 0.1 pounds per square foot per harvest. To be consistent with the 5' x 5' grow estimates, we will use a figure of 0.105 pounds per square foot per harvest.[11] At four harvests per year that suggests 1300 * 0.105 * 4 = 546 pounds per house per year (usable, dry, sinsemilla grade). Assuming 2000 labor-hours per work-year, that suggests a labor productivity of roughly 4 hours per pound grown (exclusive of harvest and processing time), or $40 per pound at a labor rate of $10 per hour.

As an aside, we mentioned above that wages of $20 - $25 per pound came up frequently in our readings. So replacing those enforcement-risk inflated wages (Reuter and Kleiman, 1986), with wages typical of conventional agricultural workers would reduce production costs by about $50 per pound, even if there is no increase in labor productivity.

Labor Cost for a Commercial Greenhouse Growing Operation
There are many variants on greenhouse operations, ranging from essentially roofed outdoor growing with large plants to typical indoor operations (small, dense planting), but using a cheaper structure and supplementing electric lights with natural light.

[11] E.g., this is the rate implied by Tooney's (2006) figures, discussed further below.

We will envision the latter, but more or less arbitrarily imagine that greenhouse-based small-plant cultivation achieves only half the productivity per square foot as does production in houses, i.e., 0.2 pounds per square foot per year. Greenhouses offer less control of lighting than purely indoor grows, but Cervantes (2006) asserts that greenhouse operations can still achieve three harvests per year, vs. four per year with pure indoor. Our rounding down from ¾ to ½ the plant productivity per square foot is meant to reflect less densely packed growing areas (e.g., more walkway space for workers).

Greenhouse operations offer important labor efficiency benefits relative to house-based growing both from scale economies and simpler lay-outs (both for people and for HVAC control). Indeed, agricultural extension service estimates of hydroponic greenhouse operations for legal crops like tomatoes and lettuce typically estimate labor costs at $2 - $5 per square foot per year (OSU, 2008; Uva and Richards, 2000), which would translate to $10 - $25 per pound at 0.2 pounds per square foot per year. That is roughly half the labor cost per pound we estimated for house-based growing, where the emphasis was on productivity per unit area not per unit of labor cost.

2.3: Rent

Rent for a Private 5' x 5' Hydroponic Grow

For the same reasons discussed under labor costs, we prefer to think of the "rent" paid on a 5' x 5' private grow as an in-kind contribution of the recreational grower. However, if one wished to impute rent for indoor small-scale growing, one could use the same figure as for commercial indoor growing, which we derive next.

Rent for a Commercial Growing Operation in a House

Conceptually this calculation is simple; we simply want to charge the rent or all-in ownership costs of a typical 1500 square foot house. California housing markets make this highly dependent on the particular location. A 1500 square foot house in Malibu costs enormously more than in rural parts of California. Hence, this aspect of production costs is difficult to predict, and is heavily dependent on which if any California localities decide to allow and regulate commercial production.

The median price of residential housing in California is roughly $300,000.[12] An old saw is that landlords should think in terms of a 100:1 ratio of purchase price to monthly rent, suggesting annual rent of $36,000. Dividing by an estimated production volume of 546 pounds per year works out to a rental cost of $66 per pound.

There are many ways this calculation could be refined. For example, marijuana growers would gravitate toward cheaper than average housing; the marijuana plants do not care

[12] http://www.businessweek.com/news/2010-05-24/california-house-prices-rise-on-fewer-foreclosures-update1-.html.

about curb appeal or school district quality. On the other hand, there would presumably be some risk of federal enforcement leading to seizure and forfeiture of the house.

Without any particular basis, we will illustrate the uncertainty of this rental cost by expressing it as a range going from half to double the $66 per pound point estimate, but caution the reader that this range should be seen as a place holder to remind us of the imprecision in the calculations. It should not be construed as a confidence interval or as lower and upper bounds.

Rent for a Commercial Greenhouse Growing Operation

Besides economizing somewhat on electricity, the great appeal of greenhouse based growing is the lower rental cost. State agricultural extension services provide return-on-investment analyses for all sorts of farming, including greenhouse based farming. While there are some differences across studies, notably concerning heating costs which vary by region, it is clear that the rent or structure costs are much, much lower in greenhouses than they are in a typical residential house.[13]

Typical greenhouse construction costs are $5 - $12 per square foot[14]. Even factoring in equipment costs and using aggressive depreciation schedules, that still leaves amortized capital cost on the order of $2 to 3 per square foot. To give a particular example, the Ohio State University Extension (2008) provides budgets for hydroponic greenhouse operations for tomatoes and lettuce. Structure and environmental control equipment for a 12,288 square foot greenhouse each total about $50,000 for either crop; growing and delivery equipment costs are higher for lettuce than tomatoes (roughly $60,000 vs. $20,000), leading to somewhat higher amortized annual fixed costs for lettuce ($2.60 per square foot) than tomatoes ($1.97 per square foot).[15]

For a second example, consider Uva and Richards' (2000) estimates of average costs for greenhouses in New York State. The overall cost of $13.46 per square foot per year was dominated by labor ($3.87 per sq. ft. per year), plants, materials, etc. – all things we

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[13] One disadvantage of greenhouses is that they might be more vulnerable to being burglarized. Sellers of expensive illegal drugs (cocaine, heroin, etc.) are robbery targets because their drugs have high value per unit weight (akin to why electronics and jewelry make better theft targets than furniture) and the drug sellers cannot call the police. It is not clear how this would play out for greenhouse-produced marijuana post-legalization. If wholesale prices are in the range of $350 per pound, that is more valuable per unit weight than a laptop computer but less than a cell phone. It is also not clear whether greenhouse operators would feel free to call the police or whether greenhouse operators' property insurance policies would cover theft of marijuana. We ignore this issue of burglary risk in part because it is so hard to quantify and also because in the end we base our post-legalization cost estimate on production in houses, not greenhouses.

[14] This is for the modern double polyethylene style greenhouse. Classic glass-pane greenhouses are more expensive, on the order of $30 per square foot to build, and so are now less commonly built.

[15] Both figures are for total area of the greenhouse, amortizing at 20% per year. OSU (2008) assumes 90% space utilization so the costs per square foot utilized for plant growing are about 10% higher.

consider elsewhere. The components of amortized fixed costs were land rent ($0.08 per square foot per year), interest and depreciation on the structure ($0.90), property taxes ($0.14), insurance ($0.38), building repairs ($0.16), and lease/rental and repair costs on capital equipment ($0.40). Adjusting for inflation and rounding up, they total roughly $2.75 per square foot per year in current dollars.

One might worry that these studies understate land costs in California. (Land rent in the OSU calculations was only $240-300 per acre per year.) . However, even if the rental cost on land were $1,000 per acre per year (which is high for the state, but may be appropriate for some counties) and only 25% of that land could be used effectively for crop production, the land rental would still be less than $0.10 per square foot ($1000 / 25%) / 43,560 square feet per acre = $0.09 per square foot).

Given the assumptions above for greenhouse productivity of 0.1 pounds per square foot per harvest and two harvests per year, the $2 - $3 per square foot per year cost translates to $10-15 per pound.

2.4: Summary

Table 1 summarizes the considerations above concerning the production cost per pound of marijuana (specifically sinsemilla) for the three indoor production modalities.

Table 1: Estimated Post-Legalization Production Costs for Three Indoor Marijuana Production Methods

	5' x 5' indoor "hobbyist"	In a 1500 square foot residential house	1 acre 50% covered with greenhouses
Production Statistics			
Production Intensity (lbs/sq ft per yr)	0.42	0.42	0.21
Square feet cultivated	25	1300	21,780
Annual Production Rate (lbs)	10.5	546	4574
Cost per Pound Produced			
Materials (Exclusive of lighting)	$150	$50 - $150	$50 - $150
Lighting	$75	$75	$0 - $25
Labor Grow	In-kind Donation	$40	$10 - 25
Structure/Rent	In-kind Donation	$33 - $132	$10 - 15
Total cost per pound produced	$225 + In-kind	$200 - $400	$70 - $215

3. OUTDOOR CANNABIS PRODUCTION

3.1 Production Costs per Acre for (Challenging) Legal Crops[16]

This subsection aims to shed light on the cost of outdoor cannabis cultivation when all of the mechanization and technology of modern industrial agriculture can be brought to bear by considering production costs for legal agricultural products that might be deemed comparable in some sense. It is important to emphasize that these estimates would pertain to what might happen if production could proceed entirely above board, without concern about even federal law enforcement. It is not clear whether the Drug Enforcement Administration would or would not enforce federal marijuana laws against farmers operating so brazenly, even what they were doing was fully legal with respect to California state and local regulations.[17]

We picked as comparators cherry tomatoes, asparagus and leaf lettuce, all crops currently produced in California. Cherry tomatoes are similar to cannabis in that they are first grown as seedlings in a greenhouse and transplanted by hand into the field, resulting in a highly labor intensive production system. Commercial cannabis would likely be sprouted in a greenhouse similar to the tomato process to allow growers more control over the initial stages of growth (Molinar et al., 2005).

Asparagus may be relevant because commercial asparagus crowns are often grown in a greenhouse prior to being manually transplanted to the field. Asparagus and cannabis also have similar fertilizer inputs because both require a nitrogen rich soil environment (Graper and Burrows, 2001; Aegerter et al., 2007).

Leaf lettuce production is relevant because of the care required to harvest and transport the delicate crop. Similar care is taken to ensure that the crystallized buds from a cannabis plant are not compromised in the harvest (Tourte et al., 2009).

Our source of cost estimates is a series of studies produced by the University of California at Davis as a part of the Agricultural & Resource and Economics Outreach and Extension program since 2004. The program website provides PDF reports and in some cases detailed spreadsheet calculations for 153 agricultural cost studies. Each report

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[16] Carnegie Mellon Heinz College student Leigh Halverson did the initial analysis for this section.

[17] To clarify: None of the production cost estimates factor in "risks and prices" (Reuter and Kleiman, 1986) compensation for the effects of law enforcement. However, some might more readily believe that federal law enforcement could look the other way with respect to production done discreetly in a residential house, where the activity is invisible to passers-by, but have a harder time ignoring open farming visible to anyone driving down the road. Large scale green house operations present an intermediate case in terms of flagrancy/visibility; it is not obvious from the road what is being grown inside a greenhouse, but the presence of some sort of agricultural activity is unmistakable.

focuses on a specific agricultural facility in California providing a series of case studies for different fruit, vegetable, field, tree, vine crops and animal commodities.

The production costs estimated by the UC Davis studies varied from $5,600/acre for asparagus in the Imperial Valley to $18,500/acre for cherry tomatoes in the San Joaquin Valley, with lettuce falling in between ($6,400/acre in the Imperial Valley). The primary variable differentiating these estimates is labor costs. Cherry tomatoes are highly labor intensive because the seedlings are transplanted from the greenhouse and re-planted in the field by hand. Cherry tomatoes are also handpicked and sorted into three colors in the field later in the season.

It is not clear how labor intensive outdoor legal marijuana cultivation would be. Current production of cannabis is labor-intensive, but that may be because of some combination of (1) small operating scale thwarting mechanization (2) typical grey literature descriptions are of boutique quality, whereas farmed cannabis would be generic sinsemilla or even commercial grade, and (3) what Reuter (1983) terms "structural consequence of product illegality". Legalization may allow for technology innovations that will reduce labor as a percentage of total production costs. Nevertheless, to be conservative and in recognition of the fact that outdoor cannabis cultivation as practiced today often involves transplanting of seedlings, we proceed with the cherry tomato cost.

The UC Davis production cost estimates were based on fairly low rent land ($240 - $300 per acre per year). Although a proportionally small contributor to total cost of production for an expensive crop such as tomatoes, land costs are highly variable across the state of California. The rent in Shasta or Trinity County is more like $1,000 per acre per year (SOURCE). If production were legalized only in counties with such higher land values, that could increase somewhat the cost of legal marijuana production. So we round up from $18,500 to a total cost of $20,000 per acre per year.

3.2 Production Cost per Acre for Hemp[18]

Industrial hemp was widely grown legally in the past (e.g., for rope fiber) and is still grown legally in a number of countries, particularly China but also on much more limited basis in Canada (Fortenberry and Bennett, 2000). Logically, it ought to be an even better analog for estimating the cost of farming marijuana legally than are tomatoes, asparagus, or lettuce. Even though hemp and marijuana are different products, they harvested from the same species of plant.[19] The primary difference is potency; hemp varieties have lower THC content but more and longer fibers (Fortenberry and Bennett, 2004).

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[18] Carnegie Mellon Heinz College student Andrea Meyer contributed to this and the following section.
[19] Cannabis is sometimes described as including three variants: Cannabis Indica, Cannabis Ruderalis, and Cannabis Sativa. Cannabis Indica and Cannabis Sativa can both produce marijuana, hashish, and hashish oil, but only Cannabis Sativa is used to produce hemp.

However, the quality of the industrial hemp production cost estimates we identified is weaker than those of the studies of more conventional crops described above. Fewer are done by professional agricultural economists, and even those that are (e.g., Cochran et al., 2000) are inherently more speculative because they cannot base their analysis on direct observation of contemporary production in the U.S. Apart from a brief period during World War II when availability of superior alternatives (e.g., jute) was interrupted, industrial hemp has not been widely grown in the U.S. since the late 19th and early 20th centuries, and professional assessments of its economic viability in the U.S. today are not encouraging (Cochran et al., 2000).[20]

With that caveat in mind, the industrial hemp literature suggests even lower estimates of production costs than derived above, so it reinforces the overall conclusion that farmed marijuana would have production costs per pound that are very, very low compared to current prices.

NORML's web site (http://norml.org/index.cfm?Group_ID=3395) lists 17 states that authorized studies of the economic feasibility of hemp production. Several studies include production cost budgets. Cochran et al. (2000) is a relatively late study in that group and appears to be aware of the earlier studies. Cochran et al. summarize the production cost estimates as ranging from $175 to $616 per acre. (Those costs are both per acre and per year since they presume one harvest per year.)

Cochran et al. (2000) suggest that the lower estimates may have omitted land and/or fixed costs. On the other hand, studies that provided separate estimates for both hemp and seed production costs tend to find lower costs for seed production. Arguably, hemp grown for seed is the better analogy because cannabis grown for seed is more widely spaced to allow for lateral growth of branches, whereas cannabis grown for fibers are crowded together to encourage length and height (Ehrensing, 1998). The production cost of cultivating for seed is lower because this spaciousness means the grower does not buy as much seed or have as many individual plants to tend.

However, this is a distinction without a difference. If, as we suggest below, farming yields 500+ pounds of usable dry cannabis per acre, any of these hemp-based production cost estimates suggest that legal, farmed cannabis production costs could be on the order of $1 per pound. When production costs get that low, the main driver of retail price will be things other than production costs (e.g., processing, marketing, and retailing costs).

There are many reasons to be skeptical of these industrial hemp studies. First, not all the studies referenced in Cochran et al. are conducted by experienced agricultural

[20] Fortenbery and Bennett (2004) review of the literature is slightly more positive, arguing that it could compete with row crops if not specialty crops, particularly if technological innovation in harvesting and processing reduced their labor intensiveness.

economists; it is possible that some people studying the economic feasibility of industrial hemp production may have an overt or subconscious incentive to find that production costs are low, to make the industry's potential look favorable. Indeed, the cited cost estimates are far below those the UC Davis study reports for conventional agricultural products. Nevertheless, to the extent that these studies have merit, they reinforce the notion that legally farmed cannabis could produce marijuana at very low prices. Indeed, they suggest that a figure of $20,000 per acre based on cherry tomatoes may be generous by more than an order of magnitude.

3.3 Production Yield per Acre

Precise figures on yields for outdoor cannabis cultivation are difficult to come by, but we believe yields of 2,000 – 3,000 pounds of dry cannabis material per acre per year can be anticipated, of which perhaps 575 pounds per acre per year would be bud as opposed to leaves and other lower quality material.

Our primary basis is an oft-cited and not infrequently criticized study by the Drug Enforcement Administration (US DEA, 1992). It describes marijuana growing experiments conducted by the University of Mississippi that used planting densities of 9 – 18 square feet per plant (high density) and 36 – 81 square feet per plant.

The grey literature's main criticism of the study seems to be that it concluded that yields were on the order of one pound per plant, a ratio that has entered into sentencing equivalency considerations. Yields of one pound per plant are almost an order of magnitude higher than figures in the literature for indoor production, such as Toonen's 1.2 ounces per plant per harvest based on indoor growing operations in the Netherlands.

The main explanation for the difference is that outdoor plants are spaced more widely and grown to much, much larger sizes. Indoor operations seek to maximize yield per square foot, which is done by planting densely and harvesting when plants are smaller (Bouchard, 2008).[21] Also, indoor operations can produce multiple harvests per year. Outdoor operations are confined to a single harvest per year (at least in temperate areas), so letting the plants grow bigger does not carry an opportunity cost in the form of delaying planting of the next round of plants.

Also, the DEA yields are for leaves and bud, not just bud. Bouchard's (2008) estimate of 1.9 ounces per plant grown outdoors pertains to just the buds. Leaves are shunned as "commercial grade" marijuana, but they do contain THC, and processing that bulk matter to concentrate the THC is simple and amenable to efficiencies when done at scale.

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[21] High yield per square foot is particularly important today, when avoiding detection by law enforcement is a paramount concern. It would remain important for house-based cultivation after legalization not only because of the risk of federal enforcement but also simply because of cost. The calculations above show that rental costs per square foot are more than a hundred times greater for a residential house than for a farm field.

One step we took to sort out this confusion in the literature was to interview four people involved in outdoor cultivation, one of whom was able to give an extremely detailed accounting of production operation, cost, and yield over the last eight growing seasons for, in a typical year, 80 plants grown on a 50' x 100' plot. Yield in that operation was even higher (2.5 pounds per plant, usable dry) because the plants were treated more like trees in a small orchard than a field of a low-maintenance crop.

It is also worth noting that the DEA believes its figure are conservative because they are based on "oven dried" weight, and oven drying results in greater weight loss relative to wet weight than the drying methods used in the cannabis industry.

Table 2 Plant spacings and yield from the nine DEA/University of Mississippi experiments (US DEA, 1992) and our subject

	Year	Yield per Plant	Pounds per plant	Square Ft. / Plant	Pounds/Acre
High Planting Density					
Univ. of MS	1985	222 grams	0.49	9	2,369
Univ. of MS	1986	274 grams	0.60	9	2,924
DEA	1990	233 grams	0.51	18	1,243
DEA	1991	215 grams	0.47	9	2,294
Low Planting Density					
DEA-A	1990	777 grams	1.71	81	921
DEA-B	1990	936 grams	2.06	81	1,110
DEA-C	1990	640 grams	1.41	81	759
DEA	1991	1015 grams	2.24	72	1,354
DEA	1991	860 grams	1.90	36	2,294
Our contact	2001-2009	1134 grams	2.5	62.5	1,742

Table 2 summarizes the yield information. We do not believe simply averaging all the rows in the table is the right way to estimate yield. A plant spacing leaving 81 square feet per plant is excessive because that leaves vacant space between adjacent plants. It should be thought of a spacing that lets the plants grow to essentially their maximum size with minimum interference from adjacent plants. Photos of our contact's planting spaced at 62.5 square feet per plant show abundant spacing, in that case necessitated by the hillside terrain.

Instead, we base our point estimates below on the data for 9 square feet per plant; the average yield for those three lines of the table is roughly 2,500 pounds per acre. Since there are 43,560 sq. ft. per acre, that suggests 4,840 plants per acre. Multiplying 4,840

plants per acre by Bouchard's 1.9 ounce of bud per plant suggests that 575 pounds of that would be bud, and the rest leaf and other matter.

The leaf and other matter may be of little value as a finished product, at least to users looking for high-quality marijuana. However, the leaves do contain THC, and we return below to some speculations about whether methods might be developed for extracting that THC economically. If the THC content per unit weight is even one-quarter in leaves what it is in the buds (e.g., 2.5% vs. 10% THC by weight), then the leaves and other materials would contain almost half (46%) of the total THC produced.[22]

There are some other points of reference in the literature, and these suggest that our estimates based (primarily) on the DEA study are if anything conservative. Leggett (2006, p.19) provides describes cannabis resin yields of 76 – 180 grams per square meter for outdoor production in Morocco, Mexico, and South Africa. That is equivalent to 700 – 1600 pounds per acre of resin. Leggett (2006) reports that it takes 20 – 100 grams of plant material to produce one gram of resin, a far greater compression factor than occurs with producing commercial grade marijuana (e.g., 4:1 from drying). McNeill (1992) reports yields of up to 2,000 kilograms per hectare (1,784 pounds per acre) from relatively low-tech farming in Morocco. Likewise, Cochran et al.'s (2000) assessment of the viability of industrial hemp production cites other sources that mention 5 tons of hemp being produced per acre and yields of seed alone of 1,000 pounds per acre.

3.4 Production Cost per Pound

Even if cannabis production is as costly as cherry tomato growing (~$20,000 per acre) the resulting cost per pound would be quite small, although the precise ratio depends on how one prorates the cost over production of the two distinct products: 575 pounds of buds and roughly 2000 pounds of other cannabis material.

The simplest cost would be to lump the two products together and report it as $20,000 / 2500 = $8 per pound of (mostly) commercial grade marijuana.

It is important to note that this figure is more of an upper bound than a best estimate. If production costs are more like those of lettuce or asparagus ($6,000 per acre), the cost per pound falls to $6,000 / 2500 = ~$2.50 per pound. If production costs were akin to those mentioned in the industrial hemp studies, then the implied price would fall below $1 per pound.

However, whether the cost is $1 per pound or $8 per pound or even $10 per pound, the key point is that the production cost would be an order of magnitude lower than the low

[22] (2500 – 575) * 2.5% / [(2500 – 575) * 2.5% + 575 * 10%] = 46%. Cannabis quality from the user's perspective depends on more than just THC content, but we do not have information on whether the other psychoactive chemicals in cannabis are even more or not so much concentrated in buds as is the THC.

end of commercial grade prices per pound now seen in the U.S. Apparently, California-farmed legal commercial grade marijuana could outcompete commercial grade marijuana produced illegally in Mexico or in parts of the U.S. where production remains illegal.[23]

It is also interesting to think about a THC-equivalent price for marijuana whose potency is comparable to sinsemilla cultivated indoors. That is, even if outdoor cultivated marijuana buds generally had lower THC content the indoor cultivated buds, it is possible to concentrate THC extracted from other plant material that has lower THC content because resin is oil-soluble and denser than water; other leaf mater is water soluble and/or floats because it is lighter than water.

To illustrate the concept, suppose the 575 pounds of buds were 10% THC by weight and the remaining roughly 2,000 pounds were 2.5% THC by weight, and sinsemilla cultivated indoors is 15% THC by unit weight.[24] Then outdoor farming would be producing THC at a cost equivalent to producing sinsemilla for less than $30 per pound.[25] That is only about 1% of the current wholesale price. Gieringer (1994) also speculates that in the absence of taxation, the legal price of marijuana could fall by 99%.

THC-extraction would involve some cost and some loss of THC , and we have no way to estimate extraction efficiency or cost for industrial THC extraction. However, Cervantes (2006) describes a wide range of home-processing approaches, e.g., agitating leaves in a washing machine filled with ice water, supposedly yielding 3 kilograms of resin from 100 kilograms of leaf in one (14-hour) day of work.

The methods Cervantes describes are batch-based, but many would be amenable to continuous-flow operations if marijuana were legal and associated equipment would not attract enforcement attention or create a seizure risk. Such automation might greatly reduce labor effort, so we do not try to guess what it might become.

For the sake of argument, let us suppose that all of the farmed material were subject to a resin-extraction process with the efficiency Cervantes describes, and the resulting resin had a THC content comparable to indoor-cultivated sinsemilla. This is probably conservative because: (1) In Cervantes' example the input was all leaf, not leaf and bud,

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[23] Domestic U.S. marijuana production focuses on high-grade types; most commercial grade marijuana is thought to be imported.

[24] These are round numbers that are roughly consistent with University of Mississippi (20XX) potency data. They list sinsemilla buds' potency as 10.81%, which is presumably an amalgam of indoor and outdoor grown buds. The 2.5% THC content for leaves is what the University of Mississippi reports for "marijuana" leaves; for the small number of "sinsemilla loose leaf" observations they report a higher average potency of 4.12%, so using 2.5% may be conservative.

[25] At the assumed THC contents, 575 * 10% + 1925 * 2.5% = 105.6 pounds of THC, which is the amount of THC in 105.6 / 15% = 704 pounds of sinsemilla that is 15% THC. $20,000 production cost / 704 pounds = $28.40 per pound.

(2) resin often has higher content than sinsemilla, and (3) mechanization and continuous processing might well produce higher conversion rates as well as labor savings.

Even with these conservative assumption, $8 per pound farmed material converted into resin at a 100:3 ratio would imply costs of $265 per pound for material that had the THC content of indoor-cultivated sinsemilla, ignoring capital and labor costs of the processing. This at the low end of the indoor sinsemilla production cost estimates derived above. Of course if the farming costs were lower, akin to lettuce or asparagus not cherry tomatoes, the corresponding cost of this material would also be lower, below $100 per pound.

Hence, it is entirely possible that if marijuana production were truly legal in all respects, then farm-based THC-equivalent products might outcompete indoor production on a THC-equivalent basis.

4. COSTS FOR PROCESSING LEGAL CANNABIS

Cannabis is not sold in raw form; it needs to be processed before use. We take two approaches to estimating the cost of processing legal cannabis. The first is to take current sinsemilla processing methods under an illegal framework, adjust for plausible efficiency improvements, and substitute wage rates typical of legal agricultural product processing. The second is to use legal tobacco processing as a proxy for legal cannabis processing costs. Plausibly the first is more relevant for sinsemilla, whereas the second may only be informative for commercial grade marijuana processing.

4.1 Current Costs of Processing Sinsemilla[26]

It is clear that labor dominates the cost of processing sinsemilla. The materials costs are relatively minor. We tried but failed to locate good, citable estimates on the total labor effort needed to process sinsemilla today. Calls to various materials providers seemed to provide estimates that centered around seven hours per pound, but we were unable to establish the provenance or reliability of such an estimate. The figure does not seem implausible if, as appears to be conventional wisdom, the "manicuring" stage is the most labor intensive step, since we have at least bits of information about labor intensity of that step.

It is perhaps useful to distinguish three general processing stages: harvesting, manicuring, and drying/curing.

Harvesting by hand is somewhat labor intensive, involving a number of steps (typically these include trimming the plant near its base, hanging it upside down to allow the plant to dry, trimming larger leaves, etc.). It seems plausible that this could be mechanized if

[26] Carnegie Mellon Heinz College student Alex Brant contributed original research to this section.

the marijuana were grown in farm fields, but might not change substantially for legal indoor growing.

For sinsemilla, the subsequent step of "manicuring" (trimming smaller leaves from the cannabis buds) may be the most labor intensive step. This is now done with any of three levels of technology: manually with scissors, manually with an automatic trimmer, or mechanically. According to Cervantes (2006), who provides many photos of this and other processing stages, it takes four to six hours per pound of cannabis with scissors vs. one to two hours with an automatic trimmer.

Processing speeds for mechanical trimmers are unknown; promotional claims mention five to ten pounds per hour for machines such as "The Twister" (www.trimscene.com). Two feasible ways to improve understanding would be (1) collecting field observation data on processing rates with current machines and (2) engaging mechanical and food processing engineers to judge what would be possible with a serious development investment by professional engineers, as opposed to the home workbench design and fabrication technology embodied in something like "The Twister". Time and resource limitations precluded our taking either step. We somewhat arbitrarily assume that the current processing rate is one pound per hour, to allow for exaggerated marketing claims, multiple operators, and/or secondary trim by hand. However, we guess that three to five pounds per hour may be possible after legalization, on the assumption that legitimate engineering firms would be willing to design and manufacture machines for a legitimate industry. Implications of these arbitrary assumptions are discussed below.[27]

The final steps are drying and curing the cannabis. Drying can be accelerated with various techniques, but in the illegal industry still typically takes days; curing takes a few days to weeks. These are not inherently labor intensive steps, but for small-scale operations create inconvenience ("set up charges") because they are done in batch mode with small batches. These steps seem amenable to substantial economies of scale if processing were done at an industrial scale post-legalization.

Table 3 attempts to combine these various bits of information. It admittedly rests on a far less scientific and empirical basis than is desirable in serious policy analysis. Table 3 only considers the labor costs of processing, but our sense is that uncertainty about those costs swamps plausible ranges of other costs of processing (e.g., materials costs), so we do not attempt to estimate those non-labor processing costs explicitly.

Table 3: Speculations About the Labor Intensity and Associated Costs of Processing Marijuana Currently and After Legalization

	Currently (While Illegal)	After Legalization

[27] Machines like the Twister are not cheap at $14,500. However, if an operation producing 500 pounds per year amortized that investment over 4 or 5 growing seasons, the amortized cost per pound falls below $10.

	Scissors	Electric Trimmers	Machines (e.g., "Twister"	Low End	High End
Labor Intensity (Hours per pound)					
Harvesting	1.5	1.5	1.5	1.5	1.5
Manicuring	5	1.5	1	0.2	1/3
Drying/Curing	1.5	1.5	1.5	0.5	1.5
Total Hours per pound	8	4.5	4	2.2	3 1/3
Wage rate	$20 – 25 per hour			$$10 per hour	
Conjectured total cost	$80 - $200 per pound			~$20 - $35 per pound	

4.2 Tobacco Processing Costs[28]

One might think tobacco could be a reasonable proxy for large scale commercial legal cannabis processing because tobacco is dried, cut, and in most cases rolled into cigarettes before being sold to consumers. If production of legal cannabis could operate on a similar business mode, it appears that processing cost could be nearly an order of magnitude below those just estimated, perhaps closer to $3 per pound.

The US Growers Tobacco Company (USGTC, 2010) site has a calculator that estimates the processing costs (receiving, grading, stemming and drying green tobacco) as $0.30 per pound of green tobacco and estimated after sale charges (storage, insurance, transportation, and agent commission) of $0.17 per pound of dry tobacco. Tobacco, like marijuana, loses weight when dried, but less dramatically. Conversion factors vary slightly by type of tobacco, but roughly one pound of wet, green tobacco leaves is the equivalent of 0.60 pounds of dry, cured tobacco ready for sale. So the total cost of processing green/wet tobacco is $0.58 per pound ($0.30 + $0.17/0.6).

In the case of cannabis, 4-5 pounds of wet cannabis equals one pound of processed product (US DEA, 1992; Cervantes, 2006). So if the cost per pound of pre-processed material remained at $0.58 per pound, the processing cost per unit of processed marijuana would be $2 - $3 per pound.[29] That figure is only one-tenth of Table 3's estimate based on minor modifications to current methods. So if tobacco processing were a reasonable analog – which it very well might not be – then the efficiencies of industrial operations might cut processing costs by another 90% above and beyond the 60-90% cost reduction Table 3 envisions from modest automation coupled with not having to pay labor a premium for participating in an illegal activity.

[28] Research for this section was done by Carnegie Mellon Heinz College student Leigh Halverson.

[29] Arguably the true comparable is more like $1.50 - $2.00 per pound because storage, insurance, and shipping are not included in Table 3's estimates.

4.3 Inspection and Regulatory Costs

The Proposition does not describe or create a regulatory framework for marijuana production; it would merely empower local governments to do so. Hence, it is very difficult to guess how if at all compliance with regulatory requirements might increase processing or cultivation costs.

The only data points of any kind we have on this are due to Dale Gieringer (2010), the director of California NORML, who observes that: (1) regulatory oversight of the Dutch medical marijuana producer Bedrocan (http://www.bedrocan.nl/english/home.html) is so stringent that its prices are higher than those in Dutch cannabis shops and (2) marijuana potency and contamination testing can be done for $100 per sample.

The cost burden of such testing and inspection demands enormously on how large a sample can be tested at once. If every ounce had to be tested individually, the cost burden at Gieringer's suggested rate would obviously be $100 per ounce. If a house-based operation producing 546 pounds per year in four equal size harvested could somehow have an entire quarter's harvest tested at once, the cost would fall below $0.05 an ounce.

This is an essentially nihilistic range, so we prefer to think of the estimates here is those that would pertain if inspection and compliance costs were merely akin to those of existing agricultural products, which is to say negligible relative to costs in the hundreds of dollars per pound.

5. SUMMARY

Before recapping numbers estimated above, it is worth stating again that this was an extraordinarily speculative undertaking. Hard data are scarce; hard data reported in refereed scientific journals are all but non-existent. This paper is simply the product of a good faith effort to cobble together bits of information floating in the grey literature. As such it is subject to greater uncertainty and error than is the norm, even in the inexact science of policy analysis.

That said, it seems clear that production costs after-legalization would be well below current prices. Indeed, it is appears that even today, despite all the inefficiencies and extra costs generated by prohibition, production costs may be well below current prices. One explanation for that might be that illegality generates high accounting profits even in steady state as compensation for the various risks of undertaking an illegal activity (c.f., Reuter and Kleiman, 1986; Caulkins and Reuter, 2010). Another is that current

marijuana prices are not sustainable, and nontrivial declines in marijuana prices may occur even if legalization does not pass in California.[30]

We attempted to estimate production and processing costs on a range of bases and for various production modalities. It is hard to say which is most relevant because no one knows how legalization will play out in California even if the proposition passes.

At one extreme, perhaps no local jurisdiction in California will allow commercial production – e.g., because the federal government threatens to withhold federal funding from any jurisdiction that does so. In that case only the non-commercial growing in a 5' x 5' area is pertinent. The estimated cost of that is $225 per pound for a successful, well-managed operation, plus in-kind contribution of labor and forgone living space. A well-managed operation of that scale could produce roughly 10 pounds per year, enough for almost 50 people at an average annual consumption rate of 100 grams per year (Kilmer and Pacula, 2009). Since $225/pound is less than one-tenth the current wholesale price of high grade marijuana (Narcotic News, 2010), even that very limited form of legalization might exert substantial downward pressure on prices if an important segment of the market uses home-grown marijuana. Indeed, a principal advantage of allowing home-grown marijuana is to siphon demand away from illegal providers.

It is not clear whether much truly commercial production would be pursued under the guise of grow one's own. On the one hand, someone producing 10 pounds per year would have surplus they could sell. On the other hand, it might be easier to obtain a medical marijuana producers permit and be free of the 5' x 5' space restriction. Perhaps the most likely scenario is that at least one jurisdiction within California would allow commercial production. And perhaps the most likely federal response would be to prevent brazen open-air farming or large greenhouse-based operations, but not to exert much effort rooting out production done discretely in private homes. This is fairly similar to what is happening in South Australia (Sutton and McMillan, 2000SOURCE)

In such circumstances we would estimate production costs for sinsemilla of $200 - $400 per pound, plus another $20 - $35 per pound for harvesting and processing. Such costs are roughly comparable to current prices per *ounce*, and are about a factor of ten lower than the current pound price for sinsemilla in the U.S.[31]

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[30] There are already media reports of sharp price declines, e.g., a May 15, 2010 National Public Radio report (available at http://www.npr.org/templates/story/story.php?storyId=126806429) which describes "hard times" in California's traditional marijuana growing regions.

[31] As Appendix C reports, ounce prices for sinsemilla in California are typically on the order of $350 - $400, and Narcotics News (2010) cites $3,000 - 4,500 per pound as a price for "high grade" marijuana in San Francisco. http://www.narcoticnews.com/Marijuana-Prices-in-the-U.S.A.php, accessed March 3, 2010.

One factor that might soften the price decline would be highly burdensome regulatory, testing, inspection, and reporting requirements. Likewise, if a $50 per ounce ($800 per pound) tax were collected, the tax would represent roughly two-thirds of the taxed purchase price for bulk sinsemilla. (Sinsemilla sold in small quantities, particularly in a service establishment such as a marijuana café where sales might have to cover overhead, wait staff salary, etc. might be considerably more expensive per unit weight, so the tax's proportion of the taxed cost would be correspondingly smaller.)

As Bond and Caulkins (2010) note, given current estimates of the cost of smuggling marijuana illegally in the U.S., production costs that low might allow California grown sinsemilla to dominate the U.S. sinsemilla market even with a $800 per pound tax. This has three implications. First, if California can collect excise taxes on marijuana bound for export to the rest of the U.S., taxes on such exports could be a much larger source of revenue than would be taxes on sales for consumption within California. Second, regardless of whether California manages to collect the excise taxes, marijuana legalization in California might depress marijuana prices throughout the lower 48 states. Third, such exports and downward pressure on prices outside of California might attract a response from the federal government.

The conclusions so far have presumed greenhouse based production would remain infeasible. If it were possible to produce marijuana in large-scale greenhouse operations, production prices could fall still further. In one respect this does not matter. Whether sinsemilla production costs are $300 per pound indoor or $150 per pound in a greenhouse or even the $30 per pound figure from one of our various outdoor farming based estimates, (1) those values are so low relative to current prices as to extend beyond where price effects on consumption can reliably be extrapolated from current data and (2) final prices may be driven more by the costs of marketing, branding, bundling, and retailing than by production, just as the production costs (typically in China) of many household goods are a modest proportion of their retail prices.

In another respect, allowing greenhouse-based production could matter. The increased natural operating scale might lead to fewer suppliers, making regulation easier. In Table 1 above, we speculated that a one-acre greenhouse operation might produce roughly ten times as much per year as would indoor production in a typical residential house. And there is nothing magical about a one-acre greenhouse operation. If the typical greenhouse farm covered 10 acres, and such farms were able to outcompete indoor production in houses, the number of producers could be a small, small fraction of the number of producers if greenhouse based growing were not allowed.

This might create an interesting tradeoff. Legalizing greenhouse-based operations, while continuing to prohibit indoor production beyond a 5' x 5' personal plot, might leave a much more concentrated industry that is easier to regulate and possibly to tax.

6. CODA: INSIGHTS CONCERNING ENVIRONMENTAL EFFECTS OF MARIJUANA LEGALIZATION

The marijuana legalization debate is dominated by considerations such as rights and liberties, budgetary considerations, and effects on use, particularly by youth. However, at various times environmental considerations are raised. For example, illegal cultivation in national parks and forests creates a certain amount of environmental damage that might be eliminated if legalization shifted cultivation to land owned by the marijuana producer, because land owners have incentives to look after the long term fertility of those lands. As a byproduct of investigating production processes and technologies we obtained some insight into the scale of some of these issues.

The overall finding is that environmental issues are relatively minor considerations. The reason, ultimately, is that even heavy marijuana users do not use quantities that are large compared to the quantities of other agricultural products. A reasonable rule of thumb is that the quantity of marijuana consumed in a country or region is 100 grams per past-year user (Bouchard, 2008; Kilmer & Pacula, 2009, UNODC, 2009). That is less than the weight of a single medium-sized apple.

To be fair, the marijuana is dried. Wet weight is 4-5 times dry weight, so annual consumption per past-year marijuana user on a wet weight basis is more like 400 – 500 grams, or essentially one pound of agricultural product per person per year. By comparison, Americans consume roughly 100 pounds of fresh fruit (of all kinds) per person per year, and the equivalent of an additional 180 pounds per year in processed forms (U.S. Apple Association, 2005).

Water consumption calculations give a sense of perspective. Cannabis is not a water intensive crop, but indoor cultivation requires attention to hydration levels, and Cervantes estimates that 16 plants will require between 10 to 25 gallons of water per week (Cervantes, 2006). Assuming plants are grown for 90-days before harvest, that is equivalent to 8 - 20 gallons of water per plant.

Toonen et al. (2006) find average yields of 1.2 ounces (33 grams) per plant per harvest, suggesting that indoor marijuana production requires about 0.24 - 0.61 gallons of water per gram of marijuana produced. At an average annual consumption of 100 grams, that is 24 – 61 gallons, or about the equivalent of flushing a standard toilet between once every month or two; clearly water consumption (at least for indoor marijuana growing) is simply not a concern.

Likewise, total area needed for marijuana production is not that large. Making precise statements is complicated by the lack of agreement in the literature about the total quantity of marijuana consumed in the U.S., either now or after legalization. In the next

few paragraphs we will use 5,000 metric tons because it is a round number that is consistent with most current consumption estimates.[32]

With an outdoor production yield of 2,500 pounds per acre (1,134 kgs/acre), 4,400 acres of crop land would be needed to serve a 5,000 metric ton U.S. market. The U.S. has 922 million acres of farmland of which a little over 300 million is harvested each year,[33] so marijuana cultivation would only require 0.0014% of harvested cropland.

Of course, outdoor farming is probably not the most likely outcome. Suppose all of the 5,000 metric tons were provided by indoor growing with a yield of 546 pounds per house. Such domestic production would require about 20,000 houses (or less since the indoor production would mostly be sinsemilla, whereas most of the 5,000 metric tons would be commercial grade). 20,000 houses is a lot of houses, but there are about 75 million owner-occupied houses in the U.S., so 20,000 is just 0.027% of the total; widespread indoor marijuana cultivation would not exacerbate homelessness or solve the hang-over from the recent housing crisis. Indeed, a recent news article reported that there were 200,000 vacant homes in the U.S. just among those that had been constructed recently.[34]

It is harder to speculate about possible spill-over effects on Mexico, if California-based production induced crop substitution there, but these calculations suggest that environmental considerations would be a relatively minor factor in an analysis of the social-welfare effects of marijuana legalization.

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[32] Gettman's (2007) is the only one that is much larger, at 9,830 metric tons. 5000 metric tons is probably substantially larger than post-legalization, indoor production because that production would be almost all sinsemilla quality, whereas currently the majority of consumption is of lower commercial grade. So 5,000 metric tons of sinsemilla grade would more than triple US THC consumption

[33] http://www.ers.usda.gov/StateFacts/US.htm

[34] http://www.bloomberg.com/apps/news?pid=20601109&sid=au67GKPyS_Dg

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