BOTEC
Analysis Corporation

Estimating Adequate Licensed Square Footage for Production

Jonathan Caulkins, BOTEC Analysis, Carnegie Mellon University
Matthew Cohen, TriQ Inc.
Luigi Zamarra

Introduction

This document and associated spreadsheet provide a guide for estimating the cultivation area needed to support a given level of cannabis production. The data is drawn from a review of the relevant literature and from interviews conducted with 16 growers. This report finds that indoor and outdoor yields average about 40 grams per square foot per harvest, but with a considerable range. Yields per square foot per year can be much higher of course, because there can be multiple harvests per year, particularly for indoor production.

If the goal is to limit a licensee's production, restricting growing area may be a useful supplemental constraint. Setting a limit that is relatively generous (say double what one might expect is required) might discourage willful gross violations of production limits, without greatly inconveniencing a responsible grower. However, trying to make growing area the binding constraint invites a range of adaptations to increase yield per square foot that would also drive up cost and might even somewhat restrict the range of varieties brought to market.

Factors Complicating Cultivation Area Estimation

Estimating cultivation area seems straightforward. For example, if each of four harvests per year yields 50 grams per square foot, then to produce 120 metric tons of marijuana annually, one needs to license 120,000,000 / (4 * 50) = 600,000 square feet.

Five factors complicate the analysis:

1) Yield figures are not standardized.

2) Yield is normally expressed per square foot harvested, and indoor marijuana grows customarily produce multiple harvests per year.

3) Yields can vary by modality (e.g., greenhouse vs. artificial lights), variety of strain, and intensity (e.g., wattage of artificial lights or type and amount of fertilizer). We use averages that account for these variables.

B A C K
O F T H E
E N V E L O P E
CALCULATIONS

4) Yields are conventionally described in terms of grams per square foot harvested, but production facilities also have ancillary spaces for seedlings, walkways, etc. A major decision point for the WSLCB, therefore, relates to whether the area-restriction applies to the entire building, all areas occupied by plants, or solely to areas occupied by mature plants that can be harvested.

5) The future mix of production strategies and associated yields is unknown and partially endogenous to WSLCB policy. For instance, if growing area is restricted, growers may have an incentive to employ higher yielding but more expensive production methods.

The Effect of Legalization on Average Yield

Growing in the U.S. has tended toward high yields per square foot because the need to avoid detection by law enforcement incentivizes a small operational footprint. However, there are some exceptions. Growers concerned about the 100-plant threshold, (qualifying the owner for a 5-year federal mandatory minimum sentence) and who have access to a large warehouse might grow 99 very large plants and spread them out to maximize each plant's yield. A more common approach is densely packing many small plants under artificial lights to mature them quickly enough to produce multiple harvests per year.

These may not represent best practices post legalization. Densely packed plants are more vulnerable to pests and disease. Furthermore, greenhouses are more economical (with cheaper structures and lower electricity costs), attested by the fact that few legal crops are grown entirely with artificial light. However, greenhouses' economic advantages disappear in winter due to heating costs. Greenhouse R-values are very low, meaning they are poorly insulated for heat, so greenhouses might not produce as many crops per year.

Hence, there is a trade-off between yield and production cost. If there is no limit on production area, one might expect greenhouse production to gain popularity due to cost considerations. However, if production area is constrained to the point that greenhouse production would leave some demand unsatisfied, growers might use their scarce growing area for production under artificial lights—unless production limits keep prices high.

There can be a similar trade-off across different modes of production under artificial lights. Some strains or varieties of cannabis yield more per square foot than others. Likewise, some mature faster, resulting in more crops per year. Similarly, increasing lighting or fertilizer intensity can increase yield. Therefore, if production area is constrained, growers might focus on the highest yielding varieties or use more lamps per square foot to boost yields—even if that constrains the range of varieties available for sale or increased electricity consumption and production cost per kilogram.

This complicates the establishment of suitable production quotas. For example, even if the WSLCB licensed the correct acreage to produce for the entire WA market at greenhouse-level yields, producers might still use all licensed and allocated space for high yield methods, if the excess production could still be sold (e.g., because "smurf and aggregate" operations carried the additional product to other states).

Using the Attached Spreadsheet as a Tool for Estimating Yield

The spreadsheet associated with this report accounts for multiple production forms and intensities. Users may enter not only the total production target (e.g., 120 metric tons), but also a description of the mix of production forms the industry is anticipated to employ. Those cells (indicated in blue in the spreadsheet) are now set to default values that represent our best guess at present, but should be updated by the WSLCB as better information on industry structure becomes available.

The spreadsheet is "preloaded" with five scenarios: (i) base case, (ii) high yield modalities, (iii) a low cost scenario, (iv) all indoor production (balanced mix), and (v) all greenhouse production.[1] Average yield varies by a factor of about 2 across the scenarios. For instance, the area needed for a target production of 120 metric tons varies from about 0.8 to 1.5 million square feet (19 – 34 acres). Of course, we would encourage the LCB to define its own scenarios as more and better information becomes available on grower behavior.[2]

Note: We set "no roof" (full sun) at 2% as a place holder, in the belief that it will account for a negligible share of production in Washington. If that proves false, then of course that parameter should be changed.

If the WSLCB tries to restrict production substantially by tightly constraining area cultivated, it should expect the industry to adapt in various ways and so achieve yields per unit area that are at the higher end of the ranges described. As a result, the WSLCB may prefer to utilize the "skewed toward high yield" in order to determine total allowable production area. Conversely, if production area were not meaningfully constrained, then the mix of production methods might trend toward modalities that produce less per square foot per year, and the "all greenhouse" scenario might be more informative.

Variables Pertinent to Yield-per-unit-area-harvested

Yield varies for three distinct types of reasons: (1) controlled variables, (2) the possibility of a partial or complete crop failure, and (3) random variation.

Besides venue (artificial lights vs. greenhouse vs. open air), controlled variables include factors such as variety, fertilizer, hydration, soil quality, pruning method,

---

[1] Scenarios can be accessed by choosing from the Excel (2010 or later) menu: Data, What-If Analysis, and Scenario Manager, then highlighting the desired scenario and clicking the "Show" button.

[2] Defining additional scenarios is easy in Excel. We would be happy to teach how if necessary.

harvest time, and lighting intensity. There are some predictable relationships, such as causation between more intense lighting and yield per unit area. Indeed, it is not uncommon to see the literature measure yield per watt rather than per square foot (e.g., Rosenthal). Other relationships are still being investigated. For example, Vanhove (2013) finds that matching the proper fertilizer to the strain type can have a substantial effect on yield. There are also factors that can affect yield post-harvest, in the drying, curing and processing phases.

Surprisingly, the grade of flower or THC potency does not necessarily play a factor in yield. A very high quality crop can have a very low yield, and a very low quality crop can have a high yield. However, since different strains have different lengths of growth cycles, limiting licensed growth square footage may encourage producers to grow those strains that have shorter growth cycles.

Crop failures can occur for a variety of reasons, including pests (mites), fungal contamination, and other miscellaneous causes. Even when the crop does not fail and the familiar control variables are held constant, there can still be variation from crop to crop. Even expert growers can have seemingly identical crops next to one another that vary in yield by 10-20%. Indeed, Vanhove et al. (2011) demonstrate that the average coefficient of variation in yield *within* a growth condition is 0.53. This is not a mystery or in any way unique to marijuana; yields in all forms of agriculture are more variable than in assembly line production.

Production potential per square foot harvested

The tables below summarize the evidence gathered for this task from the literature and 16 interviews with growers.[3] Indoor and outdoor yields average about 40 and 47 grams per square foot, respectively, regardless of whether ranges are reduced to point estimates via arithmetic or geometric averaging.[4]

The higher value for outdoor production is due to two very high estimates. It is the interviewer's judgment that one respondent was thinking of an extreme best case scenario, and that the second may have provided an anecdotal response not supported by reliable data. Due to outlier data points, a trimmed mean may be a more reliable central measure than the usual mean. The trimmed means, omitting the two lowest and two highest estimates, are very close to 40 grams per square foot indoor or out.[5]

---

[3] The Appendix provides further information on the estimates drawn from the literature beyond that reviewed by Leggett (2006).

[4] Geometric averages – meaning the n^{th} root of the product of n numbers – have some advantages over the traditional arithmetic mean when reducing ranges to point estimates, but in this case gave essentially the same overall answer.

[5] Indeed, the trimmed mean for indoor production (40.9) is slightly larger than for the outdoor estimates (39.6), indicating just how heavily the simple average of 47 grams per sq. ft. was influenced by the two very high reports.

Source	Item/Respondent	Details of Mode	Min	Max	Arithmetic Average	Geometric Average
Indoor						
Interviewer #1	#1		20	70	45	37.4
	#2		28.375	78.03	53.2025	47.1
	#3		20	70	45	37.4
	#4		20	70	45	37.4
	#5		20	70	45	37.4
	#6		15	60	37.5	30.0
	#7		28	56	42	39.6
	#8		30	60	45	42.4
Interviewer #2	#1		30	50	40	38.7
	#2		28	42	35	34.3
	#3		41	46	43.5	43.4
	#4		20	40	30	28.3
	#5		28	36	32	31.7
	#6		23	46	34.5	32.5
Leggett (2006) review	#1	Indoor scientific	37	56	46.5	45.5
	#2	Indoor scientific	17	65	40.9	33.0
	#3	Indica/sativa 1 m indoor	37	37	37.2	37.2
	#4	Indoor ("Skunk #1")	14	28	20.9	19.7
	#5	Indoor Sea of Green	30	47	38.5	37.5
	#6	Indoor Screen of Green	70	70	70.2	70.2
	#7	Indoor Screen of Green	47	47	46.8	46.8
	#8	Unspecified indoor	63	63	63.2	63.2
	#9	Indoor hydroponics	Dropped as an outlier			
	#10	Indoors	28	56	41.8	39.4
Toonen et al. (2006)			46.9	46.9	46.9	46.9
vanHove et al. (2011)		400 Watts / sq. meter	11.6	31.45	21.5	19.1
		600 Watts / sq. meter	21.44	44.9	33.2	31.0
Knight et al. (2010)		ScrOG, successful grow	32.7	32.7	32.7	32.7
Cervantes (2006)			29.6	53	41.3	39.6
Rosenthal			25.43	62.5	44.0	39.9
		Avg across respondents			**41.3**	**38.6**
Outdoor						
Interviewer #1	#9		27.24	27.24	27.24	27.2
Interviewer #2	#1		40	70	55	52.9
	#3		93	93	93	93.0
	#4		25	50	37.5	35.4
	#5		112	112	112	112.0
Leggett (2006) review	#1	Outdoor rain-fed	14	14	14.1	14.1
	#2	Outdoor irrigated	24	24	23.6	23.6
	#3	Unspecified outdoor	14	28	21.2	20.0
	#4	Outdoor	46	46	46.5	46.5
		Avg across respondents			**47.8**	**47.2**

Production potential per square foot *licensed*

It is crucial to understand that the figures cited above are per harvest and per area harvested.

Indoor production allows 4-6 harvests per year (5 being typical), whereas outdoor production allows only 1-3 harvests per year. Thus, production per square foot per year is much higher with indoor growing.

There were no complete estimates of yields in greenhouses. One might expect the production to be comparable per harvest per square foot, but that the number of harvests per year would be somewhat lower, since greenhouse heating can be so expensive in winter months. On the other hand, air conditioning costs in the summer when growing with artificial lights can also be very high.

There is also the complicated question of ancillary space that is essential to production, but which is not itself harvested. There are three types of ancillary space:

1) Space for growing plants that are not at the harvestable stage (mother plants, seedlings, etc.).

2) Dead space that is intertwined with area to be harvested (e.g., walkways).

3) Other areas not directly involved in growing (space used for drying, storing tools, record keeping, bathrooms, etc.).

Ancillary space can easily be half as large as the canopy area that is harvested, meaning that 2/3 of a facility may be devoted to canopy.

Administratively, the simplest approach might be to license the total size of the building, which would encompass all of these types of ancillary space. However, if the license limits the sum of all these types of space, then growers will have an incentive to go to great lengths and expenses to minimize the ancillary space. For example, a grower might employ crawl space under grow tables for storing supplies and moving about. Given the high potential value of cannabis yield per unit area, such limits could justify rather extraordinary measures.

An alternative would be to license just the area devoted to mature plants. This approach would allow officials to apply the yield figures above without adjustment. However, that would require some perhaps considerable extra effort for growers and inspectors to subtract out the area of walkways when computing area under canopy. Furthermore, there is also the question of how to write a clear and consistent rule that differentiates mature plants from seedlings.[6]

---

[6] The mother plants do not require that much space in total, so folding them in with mature plants would require a relatively minor adjustment to the yield estimates above.

A third alternative would be to license total area devoted to plants, including mature plants, seedlings, and mother plants. That leaves out the third type of ancillary space, but includes the first two. In that case, the licensed area would be somewhat greater than what is occupied by mature plants, and the yield figures above would be reduced correspondingly.

Appendix A: Literature Review

From the published literature

Summary of Leggett (2006)

Leggett (2006, Table 3, pp.27-29) reviewed 35 yield estimates from a wide range of sources. Key elements of indoor estimates are reproduced below. Leggett (p.30) summarizes them as ranging from just over 300 to just under 800 grams per square meter per harvest, with an overall average of about 500 grams per square meter, with four-stage cultivation systems allowing 3-6 harvests per year.

Row	Source	Cultivation Style	Output per plant (grams)	Plants per square meter	Weight per Square Meter (grams)	Seasons per year	Output per square meter per year (grams)
#1	W. Scholten	Indoor scientific	100	4-6	400-600	4	1600-2400
#2	Br Columbia Compassion Club Soc	Indoor scientific			180-700		
#3	R. Clarke (2002, p.9)	Indica/sativa 1 m indoor	100	Assume 4	400	3-4	1200-1600
#4	R. Clarke (19998, p.189)	Indoor ("Skunk #1")			150-300 (flowers only)	3	
#5	M. Thomas (2002)	Indoor Sea of Green	9-14 (0.5 oz.)	36 (2 per sq. ft.)	324-504	4	1296-2016
#6	M. Thomas (2002)	Indoor Screen of Green	84 (3 oz.)	9	756	3	2268
#7	G. Green (2003)	Indoor Screen of Green	56 (2 oz.)	9	504	3	1512
#8	Onlinepot.org website	Unspecified indoor	170	Assume 4	680	4-52 (with CO2)	720-3400
#9	J. Cervantes (1993)	Indoor hydroponics	7	4	28	4	112
#10	Cannabis-seedbank.nl website	Indoors			300-600	3-6	

For outdoor yields, Leggett quotes Conrad in suggesting that yields of 200 grams per square meter are consistent with figures gathered from court cases in the U.S., but nonetheless uses 100 grams per square meter (one MT per hectare). Those figures would translate to 18.6 and 9.3 grams per square foot. Nonetheless, Leggett's Table 3 records some substantially greater yields, which are given here (exclusive of two described as "feral"). The sole greenhouse estimate is also included.

Row	Source	Cultivation Style	Output per plant (grams)	Plants per square meter	Weight per Square Meter (grams)	Seasons per year	Output per square meter per year (grams)
#1	UNODC Morocco	Outdoor rain-fed	76	1	76	2	152
#2	UNODC Morocco	Outdoor irrigated	4	30	127	2	254
#3	M. Starks (1990)	Unspecified outdoor	227-454	0.66	152-304	1	152-304
#4	M. Thomas (2002)	Outdoor	About 500	1	500	1	500
#5	Cannabis-seedbank.nl website	Outdoor	10-200	40 X 10 g	300-600		
#6	Cannabis-seedbank.nl website	Greenhouse		1-10	50-250	3-6	

Subsequent and Additional Citable Sources on Indoor Yield

Toonen et al. (2006) build a regression model based on 86 samples obtained from law enforcement raids in the Netherlands. Point estimate was 505 grams per square meter of dried female flower buds, which is equivalent to 46.9 grams per square foot.

Toonen et al. (2006, p.1053) also report that, "in popular cannabis cultivation literature, average yields of 366–610 g/m2 are described (11)" with the citation being to Green G. The cannabis grow bible. USA: Green Candy Press, 2001. That range is equivalent to 34.0 to 56.7 grams per square foot.

Vanhove et al. (2011) seek to improve on Toonen et al. via a growing experiment with a full factorial Latin square design, varying light intensity (400 or 600 W per sq. meter), plant density (16 and 20 plants per square meter), and plant variety (four varieties). Plants were harvested after 11 weeks. Yields were 11.6 – 44.9 grams per square foot, although the discussion states, "According to the Belgian Police, the yield figures presented in this study are below the average yield found in common illicit cannabis indoor plantations." Yields were substantially higher under the 600W condition, even slightly more than 1.5 times higher. Yields per unit area were not affected by plant density over this range. Yields did very considerably by variety. If we focus on the two higher-yielding varieties (Big Bug and Super Skunk) under the 600W condition, the average yield was 40.7 grams per square foot.

Vanhove et al. (2012) summarized more such experiments, stating: "the lower-bound of the one-sided 95% confidence interval of the yield of an indoor cannabis plantation can be set at 575 g/m^2."

Vanhove (2013, personal communications) performed a subsequent, unpublished, study interacting fertilizer type (complete scheme described in earlier papers vs. just NPK-fertilizers) crossed with variety. There was a (negative) main effect for the just NPK-fertilizer, but also a very strong interaction effect (e.g., Big Bud did better with basic fertilizer). The conclusion is that mismatching fertilizer with type can reduce yield below the 575 gram per square meter potential obtained earlier.

Knight et al. (2010) did three cycles of hydroponic growing ("Screen of Green" or ScrOG method). Each crop had six plants grown in 4.32m X 3.48 m. Production ranged from 94.2 to 186.4 ounces, which is 16.5 – 32.7 grams per square foot. Authors report problems with all three grows, due to their inexperience, particularly the two grows with lower yields. So the 32.7 gram per square foot figure would appear to the best most relevant from this study.

As an aside, the yields per plant were considerable. The authors conclude that they have demonstrated one can obtain 42 ounce per plant with THC of 30%.

Cervantes (2006, pp.148-152) describes a case study of three crops with yields of 29.6 – 53.0 grams per square foot in 10, 9, and 9 weeks, respectively.

	Crop #1	Crop #2	Crop #3
Space	16' 5" x 7' 10"	33' x 7' 10"	33' x 7' 10"
Sq. Feet	128.6	258.5	258.5
Yield (pounds)	8.4	27.6	30.2
Grams per sq ft.	**29.6**	**48.4**	**53.0**

This is consistent with his rule of thumb of "0.5g-1g/watt", which at typical light densities, equates to 31.25g-62.5g/sq. ft.

Rosenthal (Marijuana Grower's Handbook) states that "A 1000w lamp produces a yield of about 375-1000 grams." Typically a 1000w flowering lamp is used every 16 sq. ft. (4'x4'), so this translates to 23.43g-62.5g per sq. ft.

Other studies read, but not deemed relevant

McNeill (1992, p.391, "Kif in the Rif") reports outdoor production in Morocco as 2,000 kilograms per hectare, which is equivalent to 18.6 grams per square foot.

Chris Conrad (2007) Safe Access Now Online Handbook, Cannabis Yields and Dosage (Part 1-b), downloaded April 29, 2013 from http://www.safeaccessnow.net/adversitycanopy.htm.

"The typical indoor yield is 0.25 to 0.5 ounces per square foot" which would be 7.1 – 14.2 grams per square foot, but the gestalt of the overall document was an argument for liberal growing areas limits, so the author may have had an incentive to lowball yield per square foot. He relates, "About half of the area is used for flowering females … The other half is for mothers, seedlings, clones and young plants"

Amaducci et al. (2008) describe a careful agricultural experimental on yields using a completely randomized block design over two genotypes, three densities, and two harvest times, but is not really relevant since it pertained to outdoor production of cannabis for hemp. Yield in the better of the two growing seasons was close to 12 metric tons per hectare of dried stem matter, which corresponds to 111 grams per square foot. But, that is stem, so the study is worth mentioning only because it represents a true agricultural experiment.

References

Amaducci, S., A. Zatta, F. Pelatti, G. Venturi, Influence of agronomic factors on yield and quality of hemp *(Cannabis sativa* L.) fibre and implication for an innovative production system, *Field Crops Res*. 107 (2008) 161-169.

H.M.G. Van Der Werf, The effect of plant density on light interception in hemp *(Cannabis sativa* L.), j. Int. Hemp Ass. 4 (1) (1997) 8-13

Cervantes, Jorge (2006). *Marijuana Horticulture: The Indoor/Outdoor Medical Grower's Bibl*e, Van Patten Publishing, Vancouver, WA.

G. Green, The Cannabis Grow Bible: The Definitive Guide to Growing Marijuana for Recreational and Medicinal use, fourth ed., Green Candy Press, San Francisco, CA, 2001.

Knight, Glenys, Sean Hansen, Mark Connor, Helen Poulsen, Catherine McGovern, and Janet Stacey (2010). The results of an experimental indoor hydroponic Cannabis growing study, using the 'Screen of Green' (ScrOG) method—Yield, tetrahydrocannabinol (THC) and DNA analysis. *Forensic Science International,* 202: 36–44.

Leggett, T. (2006). A review of the world cannabis situation. *Bulletin on Narcotics*, Vol. LVIII, Nos 1 & 2, pp.1-155.

McNeill, J.R. (1992). Kif in the Rif: A Historical and Ecological Perspective on Marijuana, Markets, and Manure in Northern Morocco. *Mountain Research and Development*, 12(4): 389-392.

Potter DJ Duncombe P 2011. The effect of electrical lighting power and irradiance on indoor-grown cannabis potency and yield. J Forensic Sci. 2012 May; 57(3):618-22. doi: 10.1111/j.1556-4029.2011.02024.x. Epub 2011 Dec 28.

Toonen, M., Ribot, S., & Thissen, J. (2006). Yield of illicit indoor cannabis cultivation in the Netherlands. *Journal of Forensic Sciences, 51*, 1050-1054.

Vanhove, Wouter, Patrick van Damme, Natalie Meert (2011). Factors determining yield and quality of illicit indoor cannabis (Cannabis spp.) production. *Forensic Science International* 212:158-163.

Vanhove W, Surmont T, Van Damme P, De Ruyver B. (2012) Yield and turnover of illicit indoor cannabis (Cannabis spp.) plantations in Belgium. *Forensic Sci Int.* 2012 Jul 10;220(1-3):265-70. doi: 10.1016/j.forsciint.2012.03.013. Epub 2012 Apr 13.