A capture-recapture derived method to estimate cannabis production in industrialized countries

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Abstract

Background: The ubiquity of cannabis cultivation stands out against the elusiveness of its production estimates. Among the many difficulties with the cannabis industry is that methodologies that are suitable for estimating large-scale outdoor illegal drug production in developing countries cannot be used to estimate indoor production in industrialized countries. This paper proposes a new approach that overcomes some of these difficulties.

Methods: The case study is a mature cannabis cultivation industry, located in Quebec, Canada. Starting from capture-recapture estimates of the prevalence of cannabis growers, the approach combines a diverse array of police and fieldwork data sources on the dynamics of the cultivation industry to correct for typical errors in the assumed productivity rates of different cultivation sites.

Results: Findings show that indoor cultivation sites obtain a mean yield of 1.2 ounces per plant, whereas the yield is 1.9 ounces for plants grown in outdoor settings. Indoor growers also reported using yield-per-watt (mean of 0.5 grams per watt) and yield-per-lamp (mean of 14 ounces per lamp) to assess the productivity of their cultivation site. Using these three different approaches to productivity, it was estimated that Quebec cannabis production was approximately 300 tons in 2002, 10% of which was seized by the police, 33% was consumed within the province, and 57% was potentially exported to the US. Estimates show that more than 93% of production was concentrated in less than 34% of cultivation sites.

Conclusion: The method provided conservative and empirically-based estimates of the size of the cannabis industry, shedding light on the reasons why previous estimates often appear to be too high. The actual numbers have policy implications. For one, the fact that Quebec exports more cannabis than is consumed by local users should significantly lower expectations of what can be accomplished through eradication programs.

Key Words: Cannabis – Cannabis Cultivation – Illegal Drug Markets – Capture-recapture Methodologies – Illegal Drug Production Estimation

1. Introduction

Cannabis cultivation is widely dispersed throughout the world—to a point that any distinction between "consuming" and "producing" countries is now meaningless. The 2006 *World Drug Report* identified 176 countries where cannabis is produced. In stark contrast, coca leaf production was reported in only six countries (United Nations Office for Drugs and Crime (UNODC), 2006). The ubiquity of cannabis cultivation stands out against the elusiveness of its production estimates. The academic community either prudently refrains from producing any numbers for cannabis production (e.g. Rhodes *et al*., 2001), or legitimately questions the feasibility of such estimation endeavors, especially in the case of cannabis (Reuter, 1996; Reuter and Greenfield, 2001). When estimates are provided, they are labeled as being either "highly tentative" or "informed guesses" on the size of the industry (Bureau of International Narcotics and Law Enforcement (BINLE), 2006; UNODC, 2006; Drug Availability Steering Committee (DASC), 2002).

Methodologies that are suitable for estimating large-scale outdoor illegal drug production in developing countries—such as aerial surveys of drug plantations,[1] cannot be used to estimate "production which is carried out in secrecy, in small and dispersed plots, and frequently indoors" (Reuter and Greenfield, 2001: p. 165). The alternative of extrapolating total production from seizure data is also unsatisfactory. First, there is no data for the seizure rate of domestic marijuana production, how it varies from country to country or from one year to the next. One recent example is sufficient to make this point clear. Currently, the "best estimate" of U.S. domestic marijuana production is 10,000 metric tons, assuming a seizure rate of 17.5%. It was produced in 2002 by the Marijuana Availability Watch Group (MAWG), a consortium of researchers and analysts sponsored by the UNODC (see DASC, 2002). To illustrate the malaise with the 10,000 ton estimate, consider that the best estimates of U.S.

[1] The only survey for cannabis is carried in Morocco and it is particularly well-done (UNODC, 2007). Satellite pictures are taken of all major cultivation provinces to estimate yield per hectare. Then, a sample of these sites and estimates are cross-checked on the ground by a group of researchers to assess their validity.

consumption are between 1000 and 2500 metric tons (Childress, 1994; Rhodes *et al.*, 2001), and that authorities report seizing a similar amount of domestic cannabis each year (UNODC, 2006). To accept the 10,000 ton estimate, it would be necessary to assume that the United States produces 4 to 10 times more cannabis than it needs to cover domestic consumption—implying that the United States is a very active exporter of cannabis. This is highly implausible given the important quantities of Mexican and Canadian cannabis seized within the U.S. and at its borders (NDIC, 2005; DASC, 2002).

As it shall be demonstrated in the paper, the problem is not just that we do not know what the seizure rates are, but that there are many reasons to believe that the reported amount of marijuana seized is overly inflated to begin with. This is not due to any intentional false reporting by the different law enforcement agencies, but rather because of an accumulation of incorrect assumptions in calculating the proportion of marketable product from one cannabis plant. For example, the MAWG discusses different options to establish a yield per cannabis plant, ranging from a low of 12.5 ounces to a high of 35.7 ounces (or 1 kilogram, DASC, 2002). Growers interviewed for the purpose of the current study would be very happy if these numbers were in the range of possibilities. In reality, even the most experienced growers rarely obtain more than two ounces of marketable cannabis per plant.

Thanks to a handful of recent studies, we now have a better knowledge of the kind of productivity rates that can be achieved by cannabis growers in industrialized countries. Indoor growers interviewed by Hough *et al.* (2003) reported obtaining between 0.5 and 3 ounces of cannabis per plant, or an average yield of 1.5 ounces. The most systematic study in regards to yield per plant has been published in 2006 by plant researcher Marcel Toonen and his colleagues. The team analyzed 12 plant samples from 77 indoor cultivation sites in different parts of the Netherlands, and which had been seized by the police in the 24 hours preceding the analysis. Their yield estimation model takes three variables into account: plant density (number of plants per m^2), developmental stage of the flower bud, and wattage per m^2. They found that the median grow room consisted of 259 plants, with a median plant density of 15 plants/m^2, and 510 watts of growth lamps per m^2. In practice, it means that growers put an average of 15 plants under lamps of either 400 or 600 watts. The average yield per plant was 33.7 grams, or 1.2 ounces of flower buds, or 0.99 grams per watt. The study was limited to indoor cultivation sites. Thus, it remains unclear whether more or less marketable cannabis can be yielded from outdoor plants.

The current study

Taking advantage of a diverse array of data sources on the cultivation industry in a Canadian province (Quebec), the current paper addresses these shortcomings and proposes a new method to estimate the size of cannabis production in Quebec. In many ways, the method is inspired by the approach used to produce the much less controversial drug consumption estimates. First, like demand-side approaches, it starts by estimating the size of the populations involved—here, the prevalence of cannabis growers active in a given year. Even the specific estimation method used in the current paper (a capture-recapture model) has been widely used to estimate the prevalence of hard drug users (Bohning *et al.* 2004; Calkins and Atkan, 2000; Hser, 1993; Choi and Comiskey 2003; Hickman *et al.*, 1998; Smit *et al.*, 1997; Brecht and Wickens, 1993). Second, information on cultivation patterns is used to break down the population into categories, depending on growers' productivity rates and the cultivation technique that they use. This approach is analogous to breaking population of drug users into categories, according to frequency and intensity of use.

The current study develops an estimation method based on three productivity parameters: a) yield-per-plant, b) yield-per-lamp, and c) yield-per-watt. Contrary to Toonen *et al.*'s (2006) study, the fieldwork data collected for the purpose of this study does not allow to control for the effect of plant density. However, the current approach has the advantage of distinguishing each parameter according to size and cultivation technique (soil-based outdoor and indoor techniques, and hydroponics). For many reasons, the ambitions of the study are modest. First, I cannot avoid the use of a series of assumptions, and face similar difficulties as previous studies with establishing realistic parameters for aggregated populations of cannabis growers. Second, I will show how even slight variations in the assumption have important effects on the final estimates. Third, I also include more uncertain assumptions to the usual estimates, most notably that the population of cannabis growers and of cultivation sites can be approximated through capture-recapture analysis. Nonetheless, each assumption used in this paper is backed and validated by empirical research, each is conservative, and the final estimates appear to pass face-value validity tests.

2. Data

The combination of numerous data sources is necessary to estimate cannabis production. Police data on cannabis cultivation arrests are needed for the capture-recapture analysis, and data on seizures are used to approximate a distribution of cultivation sites of different sizes and techniques (outdoor, indoor-in soil, and hydroponics) for the industry as a whole. Finally, fieldwork data on the dynamics of individual production sites are required to establish key parameters relative to the productivity and division of labor involved in sites of different sizes, and using different cultivation techniques.

Arrest data on cannabis cultivation

All cannabis cultivation arrests between 2001 and 2003 were retrieved from the MIP data set (Module d'Informations Policières), which comprises all crime-related incidents in Quebec. A single arrest may contain many different criminal charges. All arrests for which the first or second charge (or most serious charges) was for cannabis cultivation were considered as “cannabis cultivation arrests.” The 5607 cannabis cultivation offenders arrested between 2001 and 2003 had a mean of 1.03 cultivation-related arrests (for a total of 5757 arrests). Arrest data distinguish between two cultivation techniques: soil-based growing (79.4%) and “soil-less” (or “hydroponics”) growing (21.8%). The total does not round to 100% because 67 offenders (1.2%) were arrested on both cultivation charges. Those offenders were randomly distributed into the two arrest distributions, respecting the relative weight of each cultivation technique in the data. Soil-based cultivation can be carried out either in outdoor or indoor settings, a distinction that is only made in seizure data. Hydroponic growing is always carried out indoors. Unless indicated otherwise, “indoor” will refer to the soil-based technique, and “hydroponic” to soil-less cultivation. The mean of arrested growers (34 years old) and the proportion of females (15%) is similar to arrest data reported elsewhere (Plecas *et al.*, 2005).

Police seizures

A second data set comprising all the seizures made by the Quebec Provincial Police [QPP] for the years 2000 and 2001 (N = 3212) was used to obtain aggregate information on the size of cultivation sites. Seizures were classified in three categories: outdoor (65%), indoor (30%), and hydroponics (5%). Soil-based techniques are over-represented compared to arrest data for two reasons. First, only 14% of outdoor and 76% of indoor seizures lead to an arrest, compared to 95% of hydroponic cases. Second, although the QPP covers 70% of the province, data from Quebec’s largest city center (Montreal) are missing from this database but are included in the MIP. There are no reasons to believe that this should have an impact on the variables for which this dataset will be used (average size of cultivation sites, and distribution of sizes per technique, see Table 1 below).

Fieldwork data

Information on the co-offending patterns and on the productivity rates of cultivation sites were obtained from a convenience sample of 20 interviewed growers who were active in the Quebec industry between 1993 and 2005. I personally interviewed 9 growers between 2004 and 2006. Growers were recruited in a variety of informal ways,[2] and interviews were conducted in cafés and pubs in Montreal and Quebec City. All interviews were tape-recorded, and respondents were asked to speak about their past—never current, if any—experiences in cannabis cultivation. Information was gathered on many topics, including details on the dynamics of their career in cannabis cultivation, and a variety of issues touching the social and economic world of cannabis cultivation. Only information on key variables regarding the co-offending patterns and productivity rates of their sites were analyzed for the purpose of this study.

I also obtained access to the written accounts of 17 interviews conducted by undergraduate students in a criminology class at Université de Montréal between 1998 and 2003. Eleven interviews were added to the sample because they contained precise information on at least two of the key parameters used in this study: the number of plants grown for a specific crop, the number of co-offenders involved from start to finish, and one or various productivity measures described in full later in the paper. The total sample of 20 growers were 95% males, they had a mean age of 27 years old, were involved on cultivation sites of 111 plants, on average, and described the cultivation patterns of 36 crops (10 outdoor, 15 indoor, and 11 hydroponics). Only crops for which growers reported different parameters (e.g. change in the number of plants, co-offenders involved, productivity rates) were added to the database.

[2] One respondent was referred by a colleague criminologist who was supervising him while he served the end of a federal sentence in a halfway house in Montreal after being found guilty of cannabis cultivation. Two other respondents were referred by a criminology student after a seminar I taught on cannabis cultivation. The six others were referred to me by mutual acquaintances after learning about the research.

Compared to arrest data, the interviewed sample comprised more males and younger growers who were involved, on average, on smaller cultivation sites.

3. Methods

Like any estimation exercises, the method described below relies on a series of assumptions and parameters that should be exposed explicitly. The first step is to come up with a reliable estimation of the prevalence of cultivation sites. The second step uses these estimates and derives a quantity of cannabis production from the cultivation patterns and productivity rates of an average cultivation site of a give type. The prevalence of sites is derived from a capture-recapture analysis of the population of outdoor, indoor, and hydroponic growers. The details of the capture-recapture analysis have been exposed in another article (Bouchard, forthcoming), so I will not provide as much detail here. For the purpose of this paper, the assumptions and calculations required for this first estimation process are summarized in Table 1. Each will be discussed briefly.

Estimating the prevalence of cannabis growers

The prevalence of growers is estimated using Zelterman's (1988) truncated Poisson estimator. If data on known arrests and re-arrests follow the Poisson distribution specified by Zelterman's model, the missing cell in the distribution should be estimated correctly, that is, the number of cannabis growers with zero arrests. For data to follow a general Poisson distribution, a number of assumptions must be respected: 1) the population under study must be closed; 2) the population has to be homogenous; 3) the probability for an individual to be observed and re-observed must be held constant during the observation period. Such assumptions when using data on criminal populations may not be respected. However, Zelterman's estimator has been shown to be robust with regard to deviations from assumptions, and successful in estimating hidden populations of drugs users (Choi and Comiskey, 2003; Smit *et al.*, 1997; Bohning *et al.*, 2004), homeless persons (Smit *et al.*, 2002), auto thieves (Collins and Wilson, 1990), and cannabis growers (Bouchard, forthcoming). It is given by:

$$(1) \qquad Z = N / (1- e^{(-2*n2/n1)})$$

Where Z is the total population, N is the total number of individuals arrested with a cannabis cultivation charge, n1 is the number of individuals arrested once, and n2 is the number of individuals arrested twice in a given time period.

TABLE 1 ABOUT HERE

Appendix A provides the arrest distribution and more specific procedure that was used to estimate the prevalence of outdoor, indoor, and hydroponic growers for 2002 presented in Table 1. Notice that hydroponic growers represented 22% of growers arrested but 27% of the total population of grower, indicating a lower risk of being arrested compared to soil-based growers.

An important underlying assumption of the method proposed here is that such estimates encompass the full population of growers. This is not necessarily the case. The estimates are based on arrest data. Thus, the correct definition is that the capture-recapture model estimates the population of growers “at risk of being arrested.” Not all growers are at risk of being arrested. For example, seizure data indicate that only 14% of police interventions on outdoor sites lead to an arrest, in which case a capture-recapture analysis might underestimate the population of growers. The population estimates presented in Table 1 were adjusted to reflect this possibility (see Appendix A), but the fairly high seizure risks (19-37%) calculated for outdoor sites (Table 1, last column) indicate that the prevalence estimates may still be too conservative. Nonetheless, the estimates appear reasonable enough to derive lower risks of seizure for the less vulnerable indoor (5-9%) and hydroponic sites (2-3%).

Median size and % of seizures

Not all growers work on sites of similar size, or share the same commercial motivations (Weisheit, 1992; Hough *et al.,* 2003). It was necessary for the current analyses to distinguish between 3 categories: personal use (1 to 20 plants), small commercial sites (21 to 100 plants), and large commercial sites (101 + plants). Reasons for this include the relatively important proportion of marijuana cultivation sites with more than 100 plants, and also because the division of labor involved in small scale and large scale operations differs according to the type of technique used as well as the size of operations. Table 1 (column 3) shows that hydroponics sites are systematically larger than sites using other techniques and that very few seizures of such sites involve less than 100 plants (19%), compared to indoor (46%) and outdoor (73%) techniques.

An important assumption of the estimation approach is that the distribution of sizes found in data on police seizures can approximate the distribution of sizes for the industry as a whole. However, it is generally suspected that larger cultivation sites are more vulnerable to police interventions, and are thus over represented in police data (e.g. Moore, 1990). This issue can first be approached by looking at the seizure risks derived from the estimates. Risks increase with size for outdoor sites—and to a much lesser extent for indoor and hydroponic sites. Moreover, much larger hydroponic sites have systematically lower risks than parallel enterprises using other techniques—suggesting that risks and vulnerability to police interventions are not straightforward matters. A second way of approaching the issue is to compare the size of cultivation sites in police data with the size reported by the cannabis growers interviewed for this study. The average number of plants grown was systematically larger in the police data set: 128 vs. 43 plants for outdoor, 372 vs. 37 plants for indoor, and 816 vs. 274 plants for hydroponic cultivation sites. There is no way of knowing whether the sample of interviewed growers is more, or less representative of the industry. In the event that police seizures overestimate the proportion of larger cultivation sites, the effect on the estimates are not obvious: increasing the median size of operations will underestimate the prevalence of active cultivation sites. However, when the time comes to estimate cannabis production, inflated average size figures will overestimate the total quantities involved per site.

Number of co-offenders for an average site

Interviewed growers were asked to report the total number of persons involved in the cultivation process: installing the equipment, daily maintenance, harvesting, and manicuring. As expected, the collected data indicates that the number of co-offenders is a function of the number of plants grown: the more plants, the more co-offenders ($r = .88$, $p < .001$). However, the function is not similar for all techniques. Regressing the number of co-offenders involved per site on the number of plants grown, I found the parameters presented in Table 2.[3] Although caution is advised in giving too much weight to parameters derived from such small samples, the results warrant two observations. First, even for smaller sites, cannabis cultivation requires a minimum of three co-offenders to be involved from start to finish. Second, hydroponic sites benefit from more important economies of scale at larger sizes, compared to other techniques (indicated by the smaller b value). Such a result is consistent with interview data. Growers report that an important difference between hydroponic and

[3] I used a simple linear regression model of the form $C = a + b*p$, where C is the number of co-offenders per site and p is the number of plants grown per site.

indoor soil-based growing is that, once installed, the former functions almost entirely on an automated system that requires little assistance.[4] In contrast, soil-based growing requires considerable daily labor to irrigate the plants, but perhaps more importantly, to change soils after each harvest—a particularly cumbersome activity at larger sizes.

TABLE 2 ABOUT HERE

Deriving an estimator for the prevalence of grow sites

The prevalence of grow sites can be derived from these parameters. From Eq 1. I derived an estimator of the number of cultivation sites:

$$(2) \qquad S = \sum (Z_i/c_i)\lambda_{i,n}$$

Where S is the annual number of cultivation sites at risk of detection, Z is the prevalence of growers of type i, c is the number of co-offenders working on a median size of type i, and λ represents the proportion of seizures for type i and of sizes n.

For example, to estimate the number of indoor sites of more than 100 plants, I divide 25,089 by 5.9 co-offenders for a median size of 360.5 plants, and then multiply by 0.54, the seizure rate for outdoor sites of more than 100 plants. I obtain a prevalence of 2301 of such cultivation sites for the year 2002, subjected to an estimated risk of seizure of 9%. For the industry as a whole, Eq. 2 estimates that 13,008 cultivation sites were active in 2002, and that 11% of them were busted by the police.

[4] But problems may occur and, in practice, growers will still visit hydroponic sites everyday.

4. Results

The results will be presented in three parts. The first section uses fieldwork data to establish the productivity rates of cultivation sites of different sizes. The second uses these measures to derive three series of estimates of cannabis production in Quebec, Canada. The third section assesses whether the estimates are plausible, comparing them with estimates on consumption, seizures, and quantity potentially exported.

Productivity measures and key assumptions

Table 3 summarizes the findings from the fieldwork data with regards to different productivity measures of cultivation sites. Growers would sometimes calculate, for example, that they produce "one ounce per plant," "one pound per lamp," or in one case, "0.8 grams per watt." However, all calculations presented in Table 3 were constructed from asking growers more straightforward questions, such as: "*How many plants did you harvest for that particular crop? How many total lamps were running at the same time? What type of lamps were they, in number of watts?*

"Plant yield" has been the most widely used parameter in the literature, either to derive a quantity of marketable cannabis from a number of plants seized by the police, or from an aerial survey of cannabis cultivation sites. A first observation from Table 3 is that outdoor cannabis plants yield more ounces per plant (1.9 ounces (oz)) than cultivation sites located in indoor settings (mean = 1.2 oz). Indoor and hydroponic growers have a tendency to grow smaller plants and buds, mainly because the vegetative and flowering periods are shorter, and plant density is higher compared to outdoor sites. In addition, most of these commercial growers are content with only harvesting the flower bud growing at the top of the plant. In contrast, outdoor plants sometimes have enough light, and for a long enough period of time, to develop buds at the bottom. The plant yields presented in Table 3 are far from those used by the police and government agencies (12.5 to 37.5 ounces in DASC, 2002), which explains why production figures extrapolated from seizure data appear to be so high.[5] However, even with the small sample of the current study, the plant yields reported by growers are directly in line with those reported in other empirical research. For example, recall that Toonen *et al.* (2006) reported a mean yield of 1.25 ounces per plant for Dutch grow rooms.

TABLE 3 ABOUT HERE

Most indoor growers prefer to discuss yield per lamp, rather than yield per plant, perhaps because it is easier. A rule of thumb used by growers is that one 600 or 1000 watt metal halide/HPS[6] lamp will produce 1 pound of cannabis, regardless of the number of plants placed under the lamp. The choice, then, is to play the “volume” or the “growth” strategy: growing numerous but smaller plants (the volume strategy); or growing less numerous but bigger plants (the growth strategy). Many believed it would ultimately make no difference. One hydroponic grower who supervised the largest production site in the sample noted that he preferred more plants (e.g. 40) over less plants (e.g. 15) under each lamp, because this meant that a bad crop (losing 20-30% of the plants) would not place undue pressure on the productivity of the remaining plants. Column 4 (plants/lamp) and column 3 (oz/lamp) illustrate the soundness of this rationale. Indoor growers obtained lower productivity rates (10 oz/lamp, or 62.5% of 1 pound) than hydroponic growers (19.7 oz/lamp, or 1.2 pounds) in part by putting less plants, on average, under each lamp (10 vs. 23 plants). On the flip side, indoor growers had a better yield per plant (1.3 oz) than hydroponic growers (1.1 oz), although the

[5] Part of the discrepancy can be explained by the way that police weigh the plants: sometimes they leave use the leaves, stems, seeds, and trunk, in addition to the buds. Only cannabis buds are marketable and sold in Quebec. Any estimation using the weight of cannabis plants, whether before or after they are dried, is meaningless in most industrial countries.

[6] Most experienced growers will switch from a metal halide to a HPS bulb when plants enter the flowering phase.

difference was not statistically significant. Furthermore, because the number plants grown per site is a central criteria used by criminal courts to assess the seriousness of cannabis cultivation offences (Plecas *et al*., 2005), the volume strategy will turn against those growers in the event of a police raid.[7]

Some growers prefer to assess productivity in specific wattage, rather than mere number of lights. In fact, one reason that may explain the higher yields per plant of indoor sites compared to hydroponic sites is that the former used more watts (62.5 vs. 39 watts/plant), on average, for any number of plants. This is the result of indoor growers using similar lamps (e.g. 1000 watts) to grow fewer plants. For this reason, the grams-per-watt ratio (0.5 gr./watt, column 5) is perhaps the best parameter to assess the productivity for indoor growing techniques. It takes both the lamps and their intensity into account.

The final important productivity parameter presented in Table 3 is more straightforward: how many crops can be harvested each year? As expected, the answer was only one for outdoor growers. Indoor and hydroponic growers reported producing a mean of three crops per year for one cultivation site. This crop frequency is the modal answer for most small-time commercial growers, such as the ones interviewed for this study. These growers start their plants in September to harvest a first crop in December, a second in March, and a last one in June, before the outdoor season. Crop frequency, however, increases with size: the mean number of crops per year was significantly higher for sites of more than 100 plants compared to others (4.4 vs. 2.5 crops per year, $p < .05$). Large commercial growers sometimes install two, or even three grow rooms at one site, giving them enough flexibility to harvest up to 8 crops per year. However, most do not harvest this many crops, simply because they stop during the summer, when the temperature and humidity reach such high levels that the

[7] As it happens, this hydroponic grower was arrested and he was held responsible for the 2000+ plants seized in the house. Had he grown 10 plants per lamp (700 plants) instead of a mean of 30 under the 70 lamps installed in the greenhouse, perhaps his jail sentence of four years would have been shorter. This is suggested by Plecas *et al*.'s (2005) study which found a significant, positive correlation ($r = .17$, .05 level) between jail time and the number of plants seized in British Columbia, Canada.

cannabis plants can easily be damaged. Growers also reported wanting to take a break from the constant surveillance required by indoor cultivation, and others mentioned that the important drop in wholesale cannabis prices after the outdoor harvests (September-October) do not make summer indoor growing worthwhile. This is supported by seizure data which indicates that indoor and hydroponic seizures reach annual lows between in July and August (less than 5% of seizures each month).

A final parameter, "plant attrition," is important in estimating cannabis production. This parameter takes into account the fact that not all seeds or cuttings placed in the ground will reach maturity. One reason is that cannabis plants can be either male or female, and that only female plants produce the buds that cannabis users will smoke. Male plants, therefore, need to be removed as soon as sex can be identified, which happens between 4 to 8 weeks after the plants are placed in soil, depending the on the specific genetics used. Approximately 50% of males and females will be grown from any bag of seeds.[8] This led Wilkins *et al*, (2002), for example, to double his estimates of the number of plants potentially grown in New Zealand.

Fieldwork data collected for the purpose of this study indicates that the assumption that 50% of all plants grown (or of all plants seized by the police) are males is an exaggeration—at least for the Quebec industry. First, most growers use cloning techniques, or buy clones from a producer. Cloning consists in taking cuttings from a female "mother plant" in order to make an exact reproduction. Close to 70% of all crops described by interviewed growers were started from female clones. The proportion would be larger, but one indoor grower reported the productivity rates of 5 different crops in which he was experimenting different seed strains. It is also important to point out that many outdoor growers, even if they

[8] Online "seedbanks" now offer special seeds, « feminized seeds », that are assumed to greatly reduce the possibility of finding male plants. This innovation is recent enough that it should not be taken into account for the current study, which is concerned with estimating cannabis production for the year 2002. Moreover, only one grower mentioned the existence of feminized seeds, but he never used them himself.

use seeds, start their plants indoor during in February or March. When the plants are moved into ground in June, the male plants have already been discarded.

Even when growers start from female plants, not all of them reach maturity. Some plants do not receive enough light (or sun) or water for efficient growth, some are eaten by small animals, and others are infested by bugs or fungus. Not all growers interviewed reported an exact proportion of plants lost in the cultivation process, but even the most experienced growers acknowledged losing plants in almost each crop. In fact, all indoor and hydroponic growers mentioned at least one fungus episode in their short cultivation career. When growers estimated plant attrition, they reported that between 60% and 95% of female plants would reach maturity. Weisheit (1992) used a 65% figure in his important study on outdoor growers in the US. Lacking precise data on this issue, I use conservative figures: a 35% loss for outdoor growers, and a 25% loss for indoor and hydroponic growers. A 15% figure will be used for the light/watt approaches because losses are already partly taken into account in the productivity measures. In other words, "every plant counts" in the yield per plant approach, but this is not the case with the other approaches. Sensitivity analyses show that the effect of modifying this particular assumption on the production estimates is small: reducing the attrition rate by 5% also reduces production estimates by approximately 5%.

Estimating the size of cannabis production

Using the information presented in Table 1 to 3 above, three different cannabis production estimates can be provided. All estimates use the same four baseline parameters: a) the prevalence of production sites per size and per cultivation technique; b) the mean size of production sites in number of plants (from seizures data); c) an attrition factor taking into account that not all plants seized by the police are female, not all will reach maturity, and not all are used for each crop; and d) the mean number of crops per year. Then, each of the three estimates uses a different yield parameter to transform plants into quantities: 1) the mean yield per plant (in ounces); 2) the mean quantity produced per lamp (in ounces); and 3) the mean quantity of cannabis produced per watt (in grams). Notice that the key parameters for estimates 2 and 3 only concern indoor and hydroponic cultivation sites. Thus, all three estimates will use the yield-per-plant parameter to estimate outdoor cannabis production.

Results of the yield-per-plant estimate are presented in Table 4. The yield per plant for a type of cultivation site has been calculated by regressing plant yield (in ounces) on the number of plants grown in fieldwork data, and applying the formula to the adjusted mean size for the industry as a whole.[9] The reason is that fieldwork data showed that plant yield decreases as a function of size. For example, the yield-per-plant estimate for large hydroponic sites is 0.9 ounces, whereas for smaller sites the yield-per-plant estimate is 1.3 ounces (Table 4). In line with the productivity rates derived from the interviews with growers, large indoor and hydroponic commercial sites were attributed a four crop-per-year ratio. The adjusted mean size simply reflects the mean number of plants seized by the police minus plant attrition. The final calculation is simple:

(3) Total cannabis production (in oz) = Prevalence*(Adj. mean size*oz/plant*crops/year)

TABLE 4 ABOUT HERE

The total yield-per-plant estimate of cannabis production in Quebec in 2002 is 302 metric tons. The last column of Table 4 shows that the minority of very large indoor and hydroponic cultivation sites account for the bulk of cannabis production in the province. According to these estimates, 93% of the amount of cannabis produced in Quebec is carried

[9] I used two regression formulas, one for outdoor sites, and one combining indoor and hydroponic sites. For outdoor sites (N = 9): Y = 2.124 – 0.00532*P, where Y is the yield per plant (on oz) and P is the number of plants grown per site. For indoor and hydroponic sites (N = 23): Y = 1.306 – 0.000587*P.

out by 34% of all active sites in the province. In contrast, outdoor production amounts to 32% of all sites in Quebec, but it accounts for a little more than 2.4% of total production. Such results are well-known in drug abuse research, where a minority of heavy users accounts for the majority of illegal drug consumption (e.g. Rydell and Everingham, 1994).

How does this 302-ton estimate compare to quantities derived from other productivity measures? Table 5 and Table 6 present the estimates for the yield-per-lamp and the yield-per-watt approaches, respectively. The yield-per-lamp estimate was calculated in three steps. First, fieldwork data was used to regress the number of plants that growers placed under each lamp on the total number of plants grown.[10] This calculation is necessary because the number of plants grown per lamp was shown to increase with size in the sample of growers (although the correlation is not significant, due to the small sample size, r = .32, n.s.). For example, in large commercial sites, growers cultivated an average of 20 (indoor) and 23 (hydroponic) plants under each lamp, whereas smaller sites had 14 plants. With that figure it is possible to calculate the number of lamps installed in a cultivation site of a given size (column 6). In addition, fieldwork data show that the quantity of cannabis obtained per lamp increases with the number of plants under each lamp (r = .86, p<.01). Thus, yield-per-lamp estimates were regressed on the plants-per-lamp ratio in fieldwork data.[11] Then, the regression formula is used to estimate the yield per lamp for the industry as a whole (column 7, Table 5). Outdoor yield-per-plant figures were used to calculate the total quantity of cannabis production presented in column 8, Table 5.

TABLE 5 ABOUT HERE

[10] The regression formula for indoor and hydroponic sites (N = 23): P/L = 13.835 + 0.0112*P, where P/L represents the number of plants per lamp, and P the number of plants grown per site.
[11] The regression formula for indoor and hydroponic sites (N = 23) : Y/L = 3.686 + 0.658*P, where Y/L is the yield-per-lamp in oz.

According to the yield-per-lamp approach, 301 metric tons of cannabis were produced in 2002. This second approach yields a strikingly similar estimate to the one found in Table 4 (302 tons). This should be expected, because both approaches share many assumptions, as well as the outdoor estimates. Yet, two important assumptions for (plants/lamp and oz/lamp) are based on very different parameters, which makes the similarity between the two approaches more interesting. One difference is that the second approach ends up giving more weight to large commercial hydroponic sites which get 54% of the share of production in the province (compared to 50% in Table 4). The yield-per-lamp approach appears to better take into account the enhanced productivity of hydroponic sites, which can produce up to 19 ounces of cannabis per lamp (column 7, Table 5).

Table 6 presents a summary of the parameters used to produce the yield-per-watt production estimates. Establishing yield parameters for wattage was more difficult because the distribution derived from the sample of interviewed growers was highly skewed. For example, one respondent reported using a 400-watt lamp for a single plant, while other growers would use the same wattage for a 20-plant crop. Logging (base 10) appeared to be a sensible solution to this problem, given the log-normal distribution of the watts-per-plant ratio in the sample, and the fact that wattage per plant is subject to the law of diminishing returns (small-time growers with very large watts-per-plant ratio only marginally increase their yield per plant). The watts-per-plant geomean (not shown in Table 6) was used for all calculations. Compared to the productivity measures presented in Table 4 and 5, the yield-per-watt ratio behaves differently (column 7, Table 6). A site's yield per watt is not correlated to the number of plants grown ($r = -.04$, n.s.), but it shows a strong negative correlation to the (log) number of watts used per plant ($r = -.68$, $p<.01$). The yield-per-watt estimate was thus derived from a linear regression model calculated with watts-per-plant estimates as the sole covariate in fieldwork data.[12]

TABLE 6 ABOUT HERE

The yield-per-watt estimate of cannabis production is the highest of all approaches at 307 metric tons. A larger estimate for large hydroponic cultivation sites (161.7 vs. 166.2) accounts for most of the difference with the yield-per-lamp approach (Table 5). Overall, all production figures remain very close to each other. Taken together, they give a range of cannabis production in Quebec of 301 to 307 metric tons annually. If one approach is preferable to the other, the yield-per-watt approach would have my vote, because it takes into account not just the number of lamps but also their intensity. However, sensitivity analyses conducted on all three approaches showed that the yield-per-watt approach was slightly more sensitive to changes in the various assumptions. The skewed distributions for wattage parameters found in the sample of interviewed growers and the increased importance that this approach places on large cultivation sites explain the volatility of the wattage estimates. But given the small difference between all three estimates, no single approach has to be chosen over the others for now. For simplicity, a 300 metric ton figure will be used for the remainder of the paper.

Comparing with alternative estimates

The 300 metric ton estimate can be used to assess the plausibility of current estimates provided by the UNODC. According to the 2006 *World Drug Report*, Canada's annual cannabis production is estimated at between 960 and 2400 metric tons. These numbers

[12] The regression formula for indoor and hydroponic crops (N = 22): Y/W = 1.42 – 0.478*W/P, where W/P represents the logged number of watts used per plant grown, and Y/W the yield per watt, in grams.

suggest that Quebec would produce either 31% or 12.5% of all Canadian production. The 960 ton estimate is more plausible (31%), but seizure data indicate that it may be too high. Between 2001 and 2003, 42% of all cannabis seized in Canada was grown in Quebec. Extrapolating from the 42% and 300 ton figures would yield an estimate of 714 metric tons of cannabis produced in Canada in 2002.

One way of assessing whether the 300 ton estimate is conservative is to compare it with the results of the current approach of extrapolating from seizure data. Unadjusted cannabis seizure figures indicate that between 80 metric tons (assuming a yield of 100 grams per plant) and 130 tons (assuming 200 grams per plant) of cannabis were seized annually in Quebec between 2001 and 2003 (RCMP, 2005). Using a seizure rate of 10% would thus estimate Quebec's production at 800 to 1300 metric tons, while a seizure of 20% would estimate the production to fall between 400 and 650 metric tons. All figures fall outside the range of estimates (301-307 metric tons) found in this study. On the other hand, using correct assumptions on yield per plant (1.4 ounce per plant, from Table 3, column 2[13]) and an attrition rate of 30% would bring the quantity of cannabis seized to 31 metric tons. In turn, the 10-20% seizure rate would then produce more plausible numbers: such an approach would estimate that between 155 and 310 metric tons of cannabis was produced in Quebec in 2002.

If the 300-ton figure is accepted, then the actual seizure rate would be 10.3 % in Quebec for 2002. This figure is much lower than the 26-31% range reported by Wilkins *et al* (2002) for New Zealand during the same time period, but there are many reasons why their seizure rate appears to be too high.[14] Interestingly, the seizure rate for plants compares to the risks of seizure calculated for cultivation sites in Quebec found in Table 1 (11.0%). The

[13] I used the aggregated figures because the differential proportion of outdoor and indoor plants seized is not specified in Canadian seizure data – contrary to U.S. data.

[14] First, Wilkins et al. (2002) underestimate the number of cannabis users by not taking into account cannabis use by adolescents under 15 years old, and adults over 45 years old. Second, they underestimate the quantity of cannabis consumption by using figures that appear too low to take heavy users into account. Because their production estimate is derived from an underestimation of cannabis consumption, the seizure rate will inevitably be too high.

seizure rate is slightly lower due to the fact that the larger hydroponic cultivation sites carry the majority of production, but have very low risks of seizure compared to other parallel enterprises (Table 1). Note that the risk of arrest for growers was about four times lower (2-5%) than the figures estimated for cultivation sites (Bouchard, forthcoming).

Comparing with consumption estimates

When attempting to estimate the quantity of illegal drug production, it is necessary to consider how results compare to consumption figures. Reconciling production and consumption figures is especially important for worldwide estimates. Assuming that researchers are better at estimating consumption, then this should be the starting point for production estimates and any substantial deviation should be treated as suspect. For example, Wilkins *et al*. (2002) derived an estimate of the size of cannabis production in New Zealand from an estimate of the size of domestic cannabis consumption. An important assumption of their approach is that New Zealand has a self-sufficient and closed cannabis production system. However, in the case of cannabis production in Quebec, the general impression is that the province is exporting important quantities to the United States. First, U.S. authorities reported seizing 30 metric tons of cannabis from Quebec and British Columbia in 2005 (NDIC, 2006). Second, all the growers I personally interviewed for the purpose of this study showed some knowledge of cannabis exportation stories in Quebec—three reported that some of the cannabis they grew was exported to the US, and one respondent reported having smuggled cannabis himself to the US on a few occasions.

Estimating cannabis consumption in Quebec or Canada is not a straightforward matter. First, the general household surveys do not ask precise questions on quantities. The prevalence of different types of users can be identified, but the quantity of cannabis used per joint, the number of consumption episodes, or the quantity of joints per episode are mostly absent from the main surveys (the drug use survey among Ontario students is the exception, Adlaf and Pagalia-Boak, 2005). Second, Canada does not participate in the Arrestee Drug Abuse Monitoring (ADAM) program, which renders prevalence figures for such populations more difficult to obtain.

Fortunately, data and analyses from other comparable countries are available and can be used to compensate for the missing Canadian data. Pudney *et al*.'s (2006) methodology to estimate illegal drug consumption in the UK was particularly well-done, and it inspired the less detailed approach taken here (note that I only had access to the results of the consumption surveys, as opposed to the raw data in Pudney *et al*'s study). The approach is as follows. First, the total number of past year users was estimated by age group from two surveys: a) Canada's 2004 general household survey on drug use for 15+ years old respondents (Adlaf *et al*., 2005), and b) Quebec's 2004 general drug use survey among high school students for the 12-14 age group (grade 7 and grade 8 students in Dubé *et al*., 2006). A past year prevalence of 946,140 12+ cannabis users was derived from these sources (Table 7, column 2). Second, the Canadian survey was used to divide this figure into categories of users: experimental users (one or two consumption episodes per year), occasional (once or twice every three months), monthly, weekly, and daily users. Each has been attributed a number of days of cannabis use per year according to the definition (column 4, table 7). Intervals could also be used to produce a low and a high estimate, but for simplicity, I used the figures suggested in the survey. Each type of users does not use similar quantities per day of use. Following Pudney *et al*.'s (2006) strategy, two quantities per day of use were attributed (column 5): 0.5 grams (a little more than one joint) per day of use for non intensive users (experimental, occasional, and monthly users), and 1.2 grams per day for more intensive users (weekly and daily users). Table 7 presents estimates for the year 2003, the year preceding the 2004 survey.

TABLE 7 ABOUT HERE

According to the figures presented in Table 7, 88.7 metric tons of cannabis was consumed in Quebec in 2003. Such an estimate means that each past year user would have used 94 grams of cannabis in 2003. Interestingly, the estimate compares to many others that were produced in other developed countries showing analogous prevalence levels. For example, Childress (1994) pointed out that attributing a proportion of 100 grams per past year user accounted for the differences between light and heavy users, and approximates quite well total cannabis consumption in the US. The 100 grams-per-user benchmark was also found in Pudney *et al*.'s (2006) thorough study. They estimated cannabis consumption at 416 metric tons for 2003-2004 in the UK, a quantity spread over about 4 million past year cannabis users.

An interesting observation from the results presented in Table 7 concerns the important market share of daily users. According to these estimates, 18% of cannabis users account for 84.5% of total consumption. The average heavy user would use close to one pound of cannabis per year, which is the equivalent of one indoor crop of 15 plants under a 600 or 1000 watt lamp. Another important observation is that the estimates presented in Table 7 do not take into account cannabis use by arrestees, or by populations that are not reachable through general household phone surveys. If Quebec arrestees's market share is assumed to be similar to the one calculated by Pudney *et al*. (2006) for the UK, about 18 metric tons should be added to Quebec's 89 ton estimate (or a 17% market share for arrestees), for a total of 107 metric tons. Thus, lacking more precise data, it is estimated that between 89 and 107 metric tons of cannabis was consumed in 2003 in Quebec. For simplicity, a 100-ton figure will be used for the remainder of the paper.

If one accepts the consumption (100 metric tons) and production estimates (300 metric tons) for 2002/2003, it is estimated that only 33% of the cannabis produced in Quebec is consumed within the province. Of the remaining 200 metric tons, 31 have been seized by the police. This means that up to 59% of total production, or 169 metric tons of cannabis was available for exports to the US, or to other Canadian provinces. Is this export figure plausible? A first approach is to look at seizure figures for Canadian cannabis in the US. The RCMP (2005) recently reported that 15.7 metric tons of cannabis originating from Canada has been seized in the US in 2003. Applying the domestic seizure rate to that figure, it can be estimated that 6.6 metric tons of cannabis (or 42%) seized in the US in 2003 was smuggled from Quebec. It can also be assumed that much larger quantities are smuggled but are not seized by US authorities. If all 169 metric tons are exported to the US, then it would mean that exported cannabis from Quebec is subject to a 4 % seizure rate. This calculation is offered as a quick way to illustrate the meaning of these numbers, but it relies on many uncertain and unverified assumptions, including the possibility that a sizable quantity of cannabis is exported to other Canadian provinces.

A second way of approaching the issue is to examine if the organization of the Quebec cannabis cultivation industry is suitable to export such large quantities to the US. One can assume that most-to-all exported cannabis comes from large commercial sites. Moreover, smugglers are unlikely to export quantities under 50 to 100 pounds at one time, and groups who specialize in exportation are likely to gather such quantities from the least number of cultivation sites possible. One 850 hydroponic plant cultivation site can produce about 850 ounces per crop, which represents more than 50 pounds of cannabis. Such sites are the most suitable to subsequent distribution to the US. Table 4 to Table 6 showed that large hydroponic cultivation sites produced 152 to 166 metric tons of cannabis annually. A reasonable assumption is that such quantities are produced by the organizations that have access to the criminal networks necessary to smuggle large quantities into the US, and that most of it is indeed exported to the US.

Conclusion

Many scholars have voiced their critiques over illegal drug production estimates published in the past, with legitimate claims on the use and misuse of the available data and concepts (Reuter, 1996; Thoumi, 2005). Their conclusions were pessimistic; they even proposed that obtaining precise estimates do not seem to be important, at least to the policy makers who command them. However, implicit in their critique is that estimates are not important until they are well-done. Even though it leaves many questions unanswered, the current paper is a contribution towards that goal.

First, the paper confirms that the yield per cannabis plant has been much exaggerated in past research on the size of the cannabis production industry, helping us understand why production estimates often appear to be too high. Growers interviewed for the purpose of this study reported harvesting between one and two ounces of saleable cannabis per plant grown, and it was shown that location matters: outdoor plants yield larger quantities than most plants commercially grown indoors. Second, the paper introduces two other productivity measures that describe well the dynamics of indoor cannabis cultivation: the yield per watt and the yield per lamp used in the greenhouse. All three measures yield production estimates that remain very close to each other, but the wattage/lamp approaches appear to better capture the enhanced productivity of large commercial sites. In addition, these productivity measures can be used to correct past and future estimates of the quantity of cannabis seized by the police. Finally, the paper by-passes one of the major difficulties of estimating the size of indoor cannabis cultivation in developed countries by first estimating the prevalence of growers from arrest data. Doing so adds an important assumption to the general approach, namely that capture-recapture analysis can approximate well the size of the populations of growers involved. The results derived from the capture-recapture pass the available validity tests, but more research on different populations and with different models is needed to establish more precisely the degree of confidence one can have in these models (also see Bouchard, forthcoming).

Despite the aforementioned empirical contributions, should the actual numbers produced in this study matter to policy makers? They should. The fact that Quebec exports more cannabis than is consumed by local users should significantly lower expectations of what can be accomplished through eradication programs. What the story presented in this paper tells us is that despite the substantial law enforcement efforts devoted to eradication, the police only manages to seize 10% of the cannabis produced in the province, a good 140 metric tons away from affecting supply for users in Quebec. A related chapter of this story is that the seizures are not necessarily distributed according to merit. Instead, the analysis shows that the larger and more productive hydroponic sites have lower risks of detection than the smaller and less sophisticated enterprises - preserving hydroponic growers' incentives to increase organizational size. Hence, the numbers imply that the current policy appears inequitable in its application, and should be revised accordingly.

The substantive conclusions of the paper still do not dissipate completely many of the uncertainties regarding such estimation exercises. As always, there is no way of knowing whether the estimates are close, far, or right on the mark. Future research should try to replicate, and improve the approach presented here. All that can be said for now is that the 300-ton estimate found in this study possesses some modest, but undeniable qualities: it is based on parameters derived from empirical research, it is more conservative than estimates provided by the authorities, it yields a reasonable seizure rate given the level of law enforcement on the industry, and it confirms Quebec as an exporting country.

Table 1. Table 1. Annual prevalence and risks of detection by type of cultivation sites, Quebec, 2002 (from Bouchard, forthcoming)

Type of cultivation site	Prevalence of growers[a]	Median size (# of plants)	Co-off/med size[b]	Percent of Cases	Prevalence of cultivation sites[c]	Mean annual # of cases	Risk of detection
OUTDOOR							
Small	14644	9	2.9	36.8%	1858	358	19.3%
Medium	14644	45	3.3	36.5%	1620	355	21.9%
Large	14644	228.5	5.5	26.6%	708	259	36.6%
INDOOR							
Small	25089	7	3.0	19.8%	1656	75.5	4.6%
Medium	25089	51	3.4	26.1%	1926	99.5	5.2%
Large	25089	360.5	5.9	54.1%	2301	206	9.0%
HYDROPONIC							
Small	14978	18	3.1	1.9%	92	1.5	1.6%
Medium	14978	59	3.4	17.2%	758	13.5	1.8%
Large	14978	485	5.8	80.9%	2089	63.5	3.0%
				TOTAL	**13,008**	**1431.5[d]**	**11.0%**

a. Adjusted prevalence figures for outdoor and indoor growers for 2002 (see Appendix A).
b. As estimated through OLS regression, using fieldwork data. See Table 2 below.
c. As estimated by Eq. (2) below.
d. The mean number of seizures for 2000-2001 is 1606. However, the number of plants was not specified in 10.8% of cases (or 174.5 per year). Adding these cases increase the risks of detection by 1.3%, or from 11.0% to 12.3%.

Table 2. Regressing the number of co-offenders involved per cultivation site on the number of plants grown

Cultivation technique	a (constant)	b	R^2	p
Outdoor (N = 10)	2.805	0.0116	.51	.02
Indoor (N = 15)	2.962	0.0082	.28	.04
Hydroponics (N = 11)	2.981	0.0057	.86	.00

Table 3. Different productivity measures of cannabis cultivation sites according to the technique used by growers

Type of cultivation site	Oz/plant	Oz/lamp	Plants/ lamp	Grams/ watt	Median Watts/ plant	Crops/ year
Outdoor (N = 10)	1.9	-	-	-	-	1.0
Indoor (N = 15)	1.3	10.0	10.3	0.4	62.5	2.6
Hydroponics (N = 11)	1.1	19.7*	23.0	0.7*	38.9	3.6
Total indoor/hydro	**1.2**	**13.8**	**15.3**	**0.5**	**49.6**	**3.0**
Total all	1.4	13.8	15.3	0.5	49.6	2.3

* p<.05

Table 4. The yield-per-plant approach to estimate cannabis production in Quebec, 2002

Type of cultivation site	Prevalence of cultivation sites	Attrition rate	Adj. mean size (plants)	Oz/plant	Crops/ year	Total production (metric tons)	% of total
OUTDOOR							
Small	1858	0.35	5.9	2.1	1	0.6	0.2
Medium	1620	0.35	31.9	2.0	1	2.8	0.9
Large	708	0.35	260.0	0.7	1	3.8	1.3
INDOOR							
Small	1656	0.25	6.0	1.3	3	1.1	0.4
Medium	1926	0.25	41.3	1.3	3	8.6	2.8
Large	2301	0.25	493.5	1.0	4	129.3	42.8
HYDROPONIC							
Small	92	0.25	12.8	1.3	3	0.1	0.0
Medium	758	0.25	47.3	1.3	3	3.8	1.3
Large	2089	0.25	747.0	0.9	4	151.7	50.2
Total	**13,008**					**301.8**	**100.0**

Table 5. The yield-per-lamp estimate of cannabis production in Quebec, 2002

Type of cultivation site	Prevalence of cultivation sites	Attrition rate	Adj. Mean size (plants)	Crops/ year	Lamps/ site	Oz/ lamp	Total production (metric tons)	% of total
OUTDOOR								
Small	1858	0.35	5.9	1	-	-	0.6	0.2
Medium	1620	0.35	31.9	1			2.8	0.9
Large	708	0.35	260.0	1	-	-	3.8	1.3
INDOOR								
Small	1656	0.15	6.8	3	0.5	12.8	0.9	0.3
Medium	1926	0.15	46.8	3	3.3	13.1	6.9	2.3
Large	2301	0.15	559.3	4	27.8	16.9	121.3	40.3
HYDROPONIC								
Small	92	0.15	14.5	3	1.0	12.9	0.1	0.0
Medium	758	0.15	53.6	3	3.7	13.2	3.1	1.0
Large	2089	0.15	846.6	4	36.3	19.0	161.7	53.7
Total	**13,008**						**301.3**	**100.0**

Table 6. The yield-per-watt approach to estimate cannabis production in Quebec, 2002

Type of cultivation site	Prevalence	Attrition rate	Adjusted mean size (plants)	Crops/ year	Wattage/ site	Yield/ watt (in grams)	Total production (metric tons)	% total
OUTDOOR								
Small	1858	0.35	5.9	1	-	-	0.6	0.2
Medium	1620	0.35	31.9	1	-	-	2.8	0.9
Large	708	0.35	260.0	1	-	-	3.8	1.2
INDOOR								
Small	1656	0.15	6.8	3	907.1	0.40	1.8	0.6
Medium	1926	0.15	46.8	3	1851.3	0.66	7.0	2.3
Large	2301	0.15	559.3	4	19,128.1	0.69	120.9	39.4
HYDROPONIC								
Small	92	0.15	14.5	3	1927.6	0.40	0.2	0.1
Medium	758	0.15	53.6	3	2120.6	0.66	3.2	1.0
Large	2089	0.15	846.6	4	28,953.7	0.69	166.2	54.2
Total	**13,008**						**306.6**	**100.0**

Table 7. Estimating the quantity of cannabis consumption in Quebec, 2003

Type of users	Number of users	% of users	Number of days of use/ year	Quantity/ day of use (grams)	Grams/ year/ user	metric tons/ year	% of total
Yearly	196,601	20.8	1.5	0.5	0.8	0.1	0.2
Occasional	235,354	24.9	6	0.5	3.0	0.7	0.8
Monthly	151,231	16.0	12	0.5	6.0	0.9	1.0
Weekly	191,875	20.3	52	1.2	62.4	12.0	13.5
Daily	171,080	18.1	365	1.2	438.0	74.9	84.5
	946,140	**100.0**				**88.7**	**100.0**

Appendix A. Estimating the prevalence of cannabis growers and their cultivation sites

The first step to estimate the population of growers is to get the distribution of arrests (captures) and rearrests (recaptures) for a specified time period. The distributions presented in Table 8. represent three years of data (2001-2003). The strategy of using a three-year unit of estimation has clear advantages. First, it gives growers a reasonable length of time to get re-arrested and to start another marijuana production. Most arrested growers in Canada are not convicted to incarceration, but when they do, sentence duration is less than 6 months (Plecas *et al.,* 2005). Second, capture-recapture methods require some minimal level of re-arrests to function, and using only one year would not generate enough re-arrests for the estimator to be used. Recidivism in marijuana growing is slower because it requires some level of organization. For indoor ventures, it can take a few weeks to find a (new) grow site, to convince other interested co-offenders, or to gather the necessary start-up capital. This is indicated in the data by the higher proportion of re-arrested offenders for soil-based growing (3,1%) than for hydroponics cultivation (1,3%). As for outdoor growers, they also must wait for the summer season to start a new cultivation site, which can slow down the recidivism process. The option of using more than three years was also considered. However, this would have violated other assumptions, basically that growers remain in the criminally active population for as long as four or five years, which would have exaggerated the average career length of non-recidivist offenders.

Because arrests accumulate over a three-year time period, the population of growers estimated is also assumed to do so. To get an average annual population for a representative year like 2002, I divided the Z estimates by three. Table 8 shows that soil-based growers are almost twice as numerous as hydroponic growers at risk of being arrested (28,102 vs. 14,978). The 1998-2002 trend showed in Bouchard (forthcoming) suggested that the population of hydroponic growers had stabilized at 15,000 after a few years of fast growth (from an estimated 8112 in 1998).

Table 8. Arrest distribution for soil-based and hydroponic cannabis cultivation, Quebec, 2001-2003

Number of arrests	Soil-based growers	Hydroponic growers
	84305	44635
	(80904 - 88004)	(38933 - 53126)
0	79880	43699
1	4303	1219
2	116	17
3	6	0
4	0	0
Annual prevalence	28102	14978

Adjusting the population of soil-based growers

An important difference between the seizure and the arrest data set is that the latter does not distinguish between outdoor and indoor soil-based growers. The distinction is important, especially for assessing the differential risks of detection. The procedure starts by establishing the proportion of soil-based growers involved in outdoor and indoor settings. Seizure data for 2000-2001 show that 68% of soil-based seizures are made on outdoor sites (2075 total cases out of 3051). Because 13.9% of outdoor seizures lead to arrest, it is estimated that 288 outdoor growers were arrested in 2000-2001 (assuming one arrested offender per case). A similar calculation for indoor growers gives 742 offenders, for a total of 1030 soil-based growers arrested, 28% of which (288) are estimated to be outdoor growers. Because the number of offenders arrested per case does not vary by type of method or location (1.3 offenders per case), it is expected that 28% of the annual population of soil-based growers will be involved in outdoor production, and the remaining 72% are indoor growers.

A second adjustment was incorporated into the figures used in this study. Capture-recapture estimates are valid models to estimate populations at risks of being arrested; these models are not designed to capture segments of a population that are shielded from arrest, if they exist. Data on seizures reveal that the majority of outdoor cultivation cases never lead to an arrest. In 2000-2001, 13.9% of outdoor seizures led to an arrest, whereas 76.3% of indoor (soil-based) and 95% of hydroponic seizure cases led to at least one arrest. Thus, prevalence estimates were adjusted to reflect the percentage of offenders affected by a seizure but never arrested, by type of technique (an inflation rate of 86.1% (or 100-13.9%) for outdoor cases, 24% for indoor ones). This adjustment is unnecessary for hydroponic growers, because almost all seizures involve at least one offender arrested. This second adjustment increased the prevalence of soil-based growers by an average of 10,000 growers per year.

References

Adlaf, E.M., Begin, P., & Sawka, E. (Eds) (2005). *Enquête sur les toxicomanies au Canada (ETC): Une enquête national sur la consommation d'alcool et d'autres drogues par les Canadiens : La prévalence, L'usage et les méfaits : Rapport détaillé*. Ottawa : Centre Canadien de lutte contre l'alcoolisme et les toxicomanies.

Adlaf, E.M., & Paglia-Boak, A. (2005). *Drug use among Ontario students 1977-2005: Detailed OSDUS findings*. Toronto: Centre for Addiction and Mental Health.

Bohning, D., Suppawattanabodee, B. Kusolvisitkul, W., & Viwatwongkasem, C. (2004). Estimating the number of drug users in Bangkok 2001: a capture-recapture approach using repeated entries in one list. *European Journal of Epidemiology*, 19, 1075-1083.

Bouchard, M. (forthcoming in 2007). A capture-recapture model to estimate the size of criminal populations and the risks of detection in a marijuana cultivation industry. *Journal of Quantitative Criminology*.

Brecht, M-L., & Wickens, T.D. (1993). Application of multiple-capture methods for estimating drug use prevalence. *Journal of Drug Issues*, 23, 229-250.

Bureau of International Narcotics and Law Enforcement Affairs (2006). *International Narcotics Control Report Strategy 2006*. Washington, DC: U.S. Department of State.

Calkins, R.F., & Atkan, G.B. (2000) Estimation of heroin prevalence in Michigan using capture-recapture and heroin problem index methods. *Journal of Drug Issues*, 30, 187-204.

Childress, M. (1994). *A system description of the marijuana trade*. Santa Monica: Rand.

Choi, Y., Comiskey, C. (2003). Methods for providing the first prevalence estimates of opiate use in Western Australia. *International Journal of Drug Policy*, 14, 297-305.

Collins, M.F., & R. M. Wilson (1990). Automobile theft: Estimating the size of the criminal population. *Journal of Quantitative Criminol*ogy, 6, 395-409.

Drug Availability Steering Committee (2002). *Drug availability estimates in the United States*. U.S. Washington, D.C.: Department of Justice.

Dubé, G., Traoré, I., & Tremblay, R. (2006). *Recueil statistique sur le tabac, l'alcool, la drogue et le jeu chez les élèves du secondaire de 1998 à 2004*. Québec : Institut de la statistique du Québec.

Gettman, J. (2006). Marijuana production in the United States. In *Bulletin of cannabis reform,* available at: http://www.drugscience.org/Archive/bcr2/MJCropReport_2006.pdf

Hickman M., Cox S., Harvey J., Howes S., Farrell M., Frischer M., Stimson G., Taylor C., & Tilling, K. (1999), Estimating the prevalence of problem drug use in inner London: A discussion of three capture-recapture studies. *Addiction*, 94, 1653-1662.

Hough, M., Warburton, H., Few, B., May, T., Man, L-H., Witton, J., & Turnbull, P. (2003). *A Growing Market: The Domestic Cultivation of Marijuana*. York: Joseph Rowntree Foundation.

Hser, Y. (1993). Population estimation of illicit drug users in Los Angeles county. *Journal of Drug Issues*, 23, 323-334.

Moore, M.H. (1990). Supply reduction and drug law enforcement. In *Drugs and Crime*, M. Tonry et N. Morris (Eds). Vol 13 of *Crime and Justice: A Review of Research*. Chicago: University of Chicago Press.

National Drug Intelligence Center (2006). *National Drug Threat Assessment 2006*. Washington, D.C.: National Drug Intelligence Center, U.S. Department of Justice.

Plecas, D., Malm, A., & Kinney, B. (2005). *Marihuana Growing Operations in British Columbia revisited (1997-2003).* Department of Criminology and Criminal Justice, University of the Fraser Valley, Abbotsford.

Pudney, S., Badillo, C., Bryan, M., Burton, J., Conti, G., & Iacovou, M. (2006). Estimating the size of the UK illicit drug market. In Singleton, N., Murray, R., Tinsley, L. (Eds), *Measuring different aspects of problem use: Methodological developments* (pp. 46-120). Home office online report 16/06, available at: http://www.homeoffice.gov.uk/rds/pdfs06/rdsolr1606.pdf

Reuter, P. (1996). The mismeasurement of illegal drug markets: The implications of its irrelevance. In Pozo, S. (Ed), *The Underground Economy*. Kalamazoo, MI: W.E. Upjohn Institute for Employment Studies.

Reuter, P., & Greenfield, V. (2001). Measuring global drug markets: How good are the numbers and why should we care about them? *World Economics*, 2, 159-173.

Rhodes W., Layne, M., Johnston, P., & Hozik, L. (2001). *What America's Users Spend on Illegal Drugs 1988-2000*. Washington, D.C.: Office of National Drug Control Policy.

Royal Canadian Mounted Police (2005). *Drug Situation in Canada – 2004*. Ottawa: Criminal Intelligence Directorate, Royal Canadian Mounted Police.

Rydell, C., & Everingham, S. (1994). *Controlling cocaine: Supply vs. demand programs*. Santa Monica: Rand.

Smit, F., Reinking, D., & Reijerse, M. (2002). Estimating the number of people eligible for health service use. *Evaluation and Program Planning*, 25, 101-105.

Smit, F., Toet, J., & van der Heijden, P. (1997). Estimating the number of opiate users in Rotterdam using statistical models for incomplete count data. In European Monitoring Centre for Drugs and Drug Addiction (EMCDDA), *1997 Methodological Pilot Study of Local Prevalence Estimates*. Lisbon: EMCDDA.

Thoumi, F. (2005). The numbers game: Let's all guess the size of the illegal drug industry! *Journal of Drug Issues*, 34, 185-200.

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

United Nations Office on Drugs and Crime (2006). *2006 World Drug Report. Vol. 1: Analysis.* United Nations Office on Drugs and Crime, New York.

United Nations Office on Drugs and Crime (2007). *Maroc: Enquête sur le cannabis 2005.* New York : United Nations Office on Drugs and Crime.

Weisheit, R.A. (1992). *Domestic Marijuana: A Neglected Industry*. New York: Greenwood Press.

Wilkins, C. Battha, K., & Casswell, S. (2002). The effectiveness of cannabis crop eradication operations in New Zealand. *Drug and Alcohol Review,* 21, 369-374.

Zelterman D. (1988). Robust estimation in truncated discrete distributions with applications to capture-recapture experiments. *Journal of Statistical Planning and Inference* 18, 225-237.