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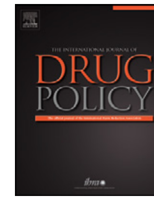

Research paper

Tracing retail cannabis in the United States: Geographic origin and cultivation patterns

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ABSTRACT

Background: Although cannabis is the most readily available and widely used illicit drug in the United States, there remains significant uncertainty about the importance of different production regions and trafficking patterns.
Methods: We analysed 628 "retail" cannabis seizures from over 50 municipalities across the United States for hydrogen and carbon isotope ratios to predict their growth locations and environments.
Results: Results are presented for 22 consolidated retail locations across the United States. Evaluation of specimens from within these retail areas suggested that cannabis seizures had region-dependent origins, often from both domestic and foreign sources, and although indoor growth was common in many areas, there was also regional dependence in the proportions cultivated under indoor versus outdoor conditions.
Conclusion: Street-available cannabis exhibits region-specific trafficking patterns, both Mexican- and Canadian-grown cannabis are apparently widely available, and indoor-grown cannabis appears to be cultivated and trafficked in both warm and cool weather localities throughout the United States.

Introduction

Cannabis (*Cannabis sativa* L.) is the most widely available illicit drug in the United States and the world. Cannabis use continues to pose significant public health threats (Di Forti, Morrison, Butt, & Murray, 2007; Gonzalez, 2007; Rey, 2008), and its increasing production on federal lands endangers public safety (Library of Congress, 2003). The cannabis sold in municipalities throughout the USA could have been grown in any number of locations: locally, transported from across the country, or imported from across borders, all either grown indoors or outdoors. Current understanding of geographic sources and movements of cannabis in the USA remains relatively poor. Although understanding drug markets is seen as essential to controlling drug related crime, and disrupting markets is a central policy goal, little research into examining the structure of USA cannabis markets has been accomplished (Caulkins & Pacula, 2006). Diagnostic tools that allow independent descriptions of the sources of cannabis are essential for unravelling market dynamics. In that regard, Ritter (2006) called for pursuing multi-disciplinary approaches to understanding drug markets. We discuss here application of a novel forensic approach to understanding the cannabis market: the use of stable isotope analyses of seized cannabis. Stable isotope analysis has the potential to significantly improve our understanding of cannabis trafficking because stable isotopes function as natural recorders revealing aspects of a plant's geographic origin and growth environment (Hurley, West, & Ehleringer, in press; West, Bowen, Cerling, & Ehleringer, 2006; West, Sobek, & Ehleringer, 2008; West, Hurley, & Ehleringer, 2009; see primer below).

Previous work has shown that stable isotope ratio data may be useful for cannabis in a forensic context (Denton, Schmidt, Critchley, & Stewart, 2001; Galimov, Sevastyanov, Kulbachevskaya, & Golyavin, 2005; Liu, Lin, Fitzgerald, Saxena, & Shieh, 1979; Shibuya, Sarkis, Negrini-Neto, Moreira, & Victoria, 2006; Shibuya, Sarkis, Negrini-Neto, & Martinelli, 2007). Our work has shown specifically that stable isotope ratio data have the potential to (1) establish links between seized specimens, (2) quantify information about growth environment and geographic origin, (3) provide information on the variety of sources supplying individual areas, as well as (4) quantify changes in the temporal distribution and cultivation practices based solely on the analysis of seized specimens (Ehleringer, West, & Hurley, 2007; Ehleringer, West, & Hurley, 2008b; Hurley et al., in press; West et al., 2009; West, Hurley, Dudas, & Ehleringer, in press). Based on the foundations established in this previous work, we report here the results of a survey of the stable hydrogen and carbon isotope ratios of retail-level cannabis seized within USA borders, with the goal of enhancing intelligence on trafficking in the country.

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An isotope primer

- Elements occur in different forms called isotopes. Isotopes differ in the number of neutrons within their nuclei. Stable isotopes persist in the same form over time, whereas radioactive isotopes decay into other elements. For example, hydrogen exists in three forms: (1) 1 proton and 0 neutrons = ^{1}H [stable]; 1 proton and 1 neutron = ^{2}H [stable]; and (3) 1 proton and 2 neutrons = ^{3}H [radioactive]. Carbon also exists in three forms: (1) 6 protons and 6 neutrons = ^{12}C [stable]; (2) 6 protons and 7 neutrons = ^{13}C [stable]; and (3) 6 protons and 8 neutrons = ^{14}C [radioactive]. The light isotopes of hydrogen (^{1}H) and carbon (^{12}C) are significantly more common, while the heavier isotopes are rare.
- Because the rare isotopes have such low concentrations in nature, the concentrations of stable isotopes are typically not measured directly. They are instead reported as ratios of the concentration of the rare (heavy) isotope relative to that of the more common (light) isotope (e.g., R = ^{2}H/^{1}H or ^{13}C/^{12}C) in a material of interest. Stable isotope abundances are generally expressed in "delta notation" (δ) in parts per thousand (‰). Delta notation specifically indicates that the reported value is the isotope ratio of the sample relative to the isotope ratio of an internationally accepted standard:

$$\delta = \left(\frac{R_{\text{sample}}}{R_{\text{standard}}} - 1\right) \times 1000.$$

An example for carbon: $-30\,‰ = \left(\frac{0.0108990}{0.0112372} - 1\right) \times 1000$

- Stable isotope ratios are typically measured using a stable isotope ratio mass spectrometer, or IRMS.

Methods

Two region-of-origin models for predicting geographic origin (Hurley et al., in press) and one cultivation model for predicting growth environment for seized cannabis (West et al., 2009) have been developed. The spatial distributions of hydrogen isotopes of precipitation across continental land masses reveal gradients of isotope ratio values due to spatially coherent climate effects on precipitation isotope ratios (Bowen & Revenaugh, 2003; Bowen, Wassenaar, & Hobson, 2005b). The cannabis region-of-origin models are based on our earlier findings that cannabis grown throughout North America reflects these spatial isotope ratio gradients (Ehleringer et al., 2007; Hurley et al., in press). It is important to note that the approaches used in the two region-of-origin models differ, with Model I predicting whether or not a cannabis specimen could have originated from one of 17 banded regions of North America, and Model II using a geographically broader approach, dividing North America into just five regions from which a cannabis specimen could have originated (Hurley et al., in press). The cultivation model establishes thresholds for indoor and outdoor-growth environments based on carbon isotope ratio measurements (West et al., 2009). Tests of these models revealed geographic predictions using Model I were 60–70% accurate, geographic predictions using Model II were 67–73% accurate, and cultivation predictions were 86% accurate (Hurley et al., in press). Our approach here is to evaluate cannabis seizures using these models to yield information about the domestic cannabis market.

Assessment of retail seizures

Between April 2007 and June 2008, we analysed 628 "retail" cannabis specimens from 52 municipalities across the USA (see Fig. 1; average specimen size 17 g), seized by USA law enforcement agencies between February 2005 and October 2007. We then evaluated the isotope ratio data using the three models to yield predictions for regions-of-origin and growth environments. Because of the high number of retail seizure locations and the interest in understanding major urban centres, seizure locations were grouped into "retail areas" representing major urban centres. These urban areas were further consolidated when they were in close proximity and fell together within one of the 17 banded regions defined by hydrogen isotope ratio values of cannabis (depicted in Hurley et al., in press). For example, Orlando and Tampa in Florida were grouped together within Region 2, and Cincinnati, Dayton and Columbus in Ohio were grouped together within Region 4. For 22 of these consolidated retail areas represented by more than 10 speci-

Fig. 1. Map showing seizure locations for the 622 coterminous USA "retail" specimens analysed. Six analysed specimens seized in Hawaii not shown.

mens, pie charts were constructed to show proportions of cannabis sourced to different geographic and cultivation categories.

Sample analysis

For all specimens from which it was possible to isolate leaf material, we analysed leaf-only fractions. For two specimens, mixed leaf and flower material was analysed instead. Generally, we pulverized approximately 50–200 mg of dried cannabis with mortar and pestle, filtering and grinding residual large particles by passing ground material through 250 μm stainless steel sieves until the complete sample was ground and homogenized. Hydrogen isotope ratio analysis was accomplished according to methods described in Ehleringer et al. (2008a). Because a percentage of hydrogen atoms (6–13%, unpublished data) in a cannabis specimen is potentially exchangeable with hydrogen atoms in atmospheric water vapour, we allowed powdered cannabis samples to equilibrate to local atmosphere for 3 days before analysis of hydrogen isotope ratios. Any resulting exchange effect should then be consistent across specimens (Bowen, Chesson, Nielson, Cerling, & Ehleringer, 2005a). After equilibration, we loaded 170 ± 17 μg of ground material into silver capsules (Costech, 3.5 mm × 5 mm, pre-combusted at 500 °C for 15 or more minutes). Hydrogen isotope ratio values (δ^2H) of cannabis specimens were measured in duplicate on a high temperature conversion/elemental analyzer coupled to an isotope ratio mass spectrometer (TC/EA-IRMS, Finnigan Delta Plus XL and Finnigan Delta V). Hydrogen isotope ratio (δ^2H) values of the cannabis specimens were corrected to a laboratory reference material (cellulose) which, along with other internal quality control materials, was also exposed to the same atmosphere and exchange conditions as the cannabis samples. Measurement precision, based on multiple analyses of the cellulose reference material, was ±2‰ for δ^2H. We re-analysed cannabis specimens with replicate δ^2H standard deviations of greater than 5‰ (those greater than approximately the 99th percentile of all standard deviations of duplicate runs). For all specimens analysed more than twice, values greater than one standard deviation from the mean of all replicates were omitted from the reported mean specimen value.

Carbon isotope ratio analysis was accomplished according to methods described in West et al. (2009). For analysis of carbon isotopes, we loaded 1.5 ± 0.15 mg of sample into tin capsules (Costech, 3.5 mm × 5 mm), and then analysed the cannabis samples in duplicate on an elemental analyzer coupled to an isotope ratio mass spectrometer (EA-IRMS, Finnigan Delta Plus). Carbon isotope ratio (δ^{13}C) values of the cannabis specimens were corrected to a laboratory reference material (yeast) that had been calibrated to an international PDB standard (belemnite carbonate from the PeeDee Formation, SC). Overall precision based on multiple analyses of the yeast reference material was ±0.1‰ for δ^{13}C. We re-analysed cannabis specimens with replicate δ^{13}C standard deviations of greater than 0.4‰ (those greater than approximately the 99th percentile of all standard deviations of duplicate runs). For all specimens analysed more than twice, values greater than one standard deviation from the mean of all replicates were omitted from the reported mean specimen value.

Results

Geographic origins of seizure specimens

Aggregated results for the 22 consolidated retail areas based on predictions using region-of-origin Model I are shown in Fig. 2. Based on Model I, many USA metropolitan areas surveyed showed high proportions of seized cannabis originated from within region. The Seattle and the Oregon retail areas, were each predicted to have

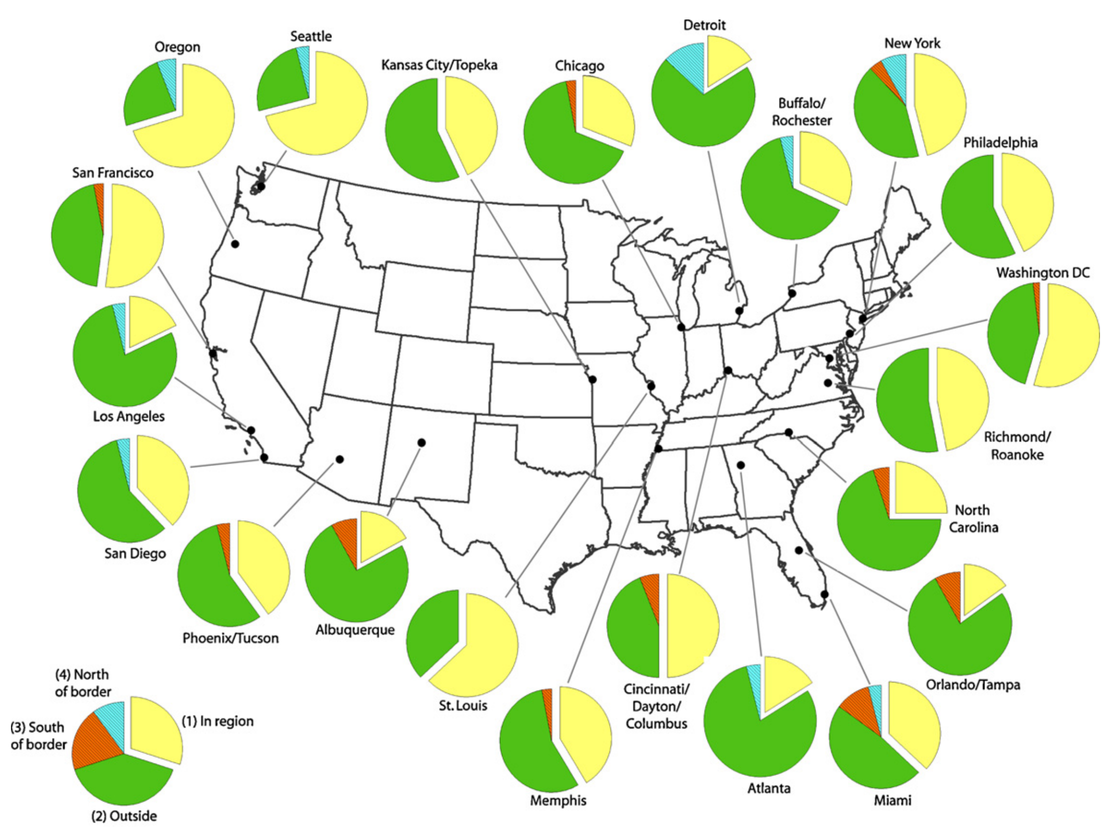

Fig. 2. Proportions of cannabis from 22 consolidated retail areas assigned to four classes of geographic origin based on region-of-origin model I—in region, outside region, north of border, and south of border.

about 70% of cannabis originating within the region. However, for other metropolitan regions the model predicted that cannabis was predominantly imported. Those metropolitan areas predicted to have had less than a quarter of the seized cannabis grown within region included (i) Los Angeles, (ii) Albuquerque, (iii) Atlanta, (iv) the Orlando/Tampa area, (v) the North Carolina retail area, and (vi) Detroit. Although foreign-derived cannabis was predicted to be small for all retail metropolitan locations, those areas closer to the northern and southern borders had relatively larger proportions identified as originating outside the coterminous USA (e.g., Miami and Detroit). On the other hand, New York City, was predicted to have among the highest proportions of cannabis derived from cross-border origins. Predictions for interior and mid-Atlantic cities, such as Kansas City, St. Louis, Memphis, and Philadelphia, indicated small proportions of cannabis originating from outside the USA. Cannabis produced south-of-the-border was predicted to occur across the country, including in the Phoenix/Tucson area, Albuquerque, San Francisco, and in cities far from the southwest border such as Chicago, New York City and Washington, DC. Cannabis produced north-of-the-border was predicted to occur in cities close to the northern border (Detroit, Buffalo/Rochester, and Seattle), all along the west coast (Oregon, Los Angeles, and San Diego), but also into the southeastern USA (Atlanta and Miami).

Aggregated results for the 22 consolidated retail areas based on predictions of isotope observations using region-of-origin Model II are shown in Fig. 3. As with region-of-origin Model I, Model II assessments of retail seizures suggest that the majority of cannabis sold in the USA is regionally derived, produced in the region in which it was seized. In general, about half or more of the seized cannabis is predicted to have originated within the region in which it is marketed. Notable exceptions to this general prediction included the Phoenix/Tucson and Albuquerque areas, where well over half of the market appears to have originated south-of-the conterminous USA southern border. In the Detroit, Atlanta and Orlando/Tampa areas, Model II predicts that about half of the market originated north-of-the conterminous USA northern border. Seattle also appears to be disproportionately impacted by cannabis predicted to have been grown north-of-the conterminous USA northern border.

Growth environments of seizure specimens

The 22 consolidated retail areas differed substantially in the fraction of seized cannabis predicted to have been indoor-grown (Fig. 4). Retail areas in northern states tended to have higher proportions of cannabis identified as indoor-grown. Almost all cities across the USA appeared to have seized cannabis that was indoor-grown. Perhaps consistent with attempts by growers to avoid law enforcement, substantial proportions of seized cannabis from a number of warm-climate cities were predicted to have been indoor-grown, including San Diego, Los Angeles, Miami, and the Orlando/Tampa metropolitan region. However, little or no indoor-grown cannabis was predicted from the Albuquerque and Phoenix/Tucson areas. This is consistent with little or no evidence of indoor-grown cannabis from seizures along the USA southwest border presumed to originate in Mexico (Ehleringer et al., 2007, 2008a,b), and contrasts with observations from California and Florida seizures, which show significant indoor growth (see Fig. 4). Some temperate areas of the Midwest were predicted to have little or no indoor-grown cannabis seizures, including the Kansas City and St. Louis areas.

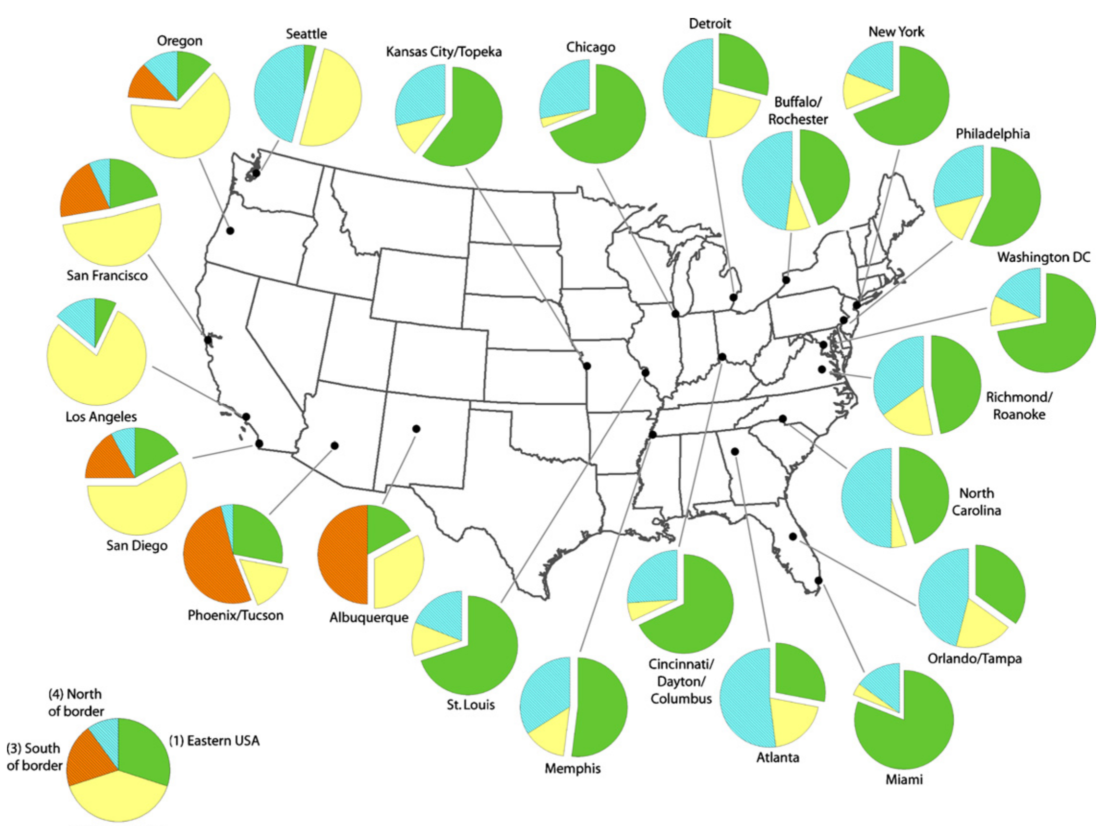

Fig. 3. Proportions of cannabis from 22 consolidated retail areas assigned to four classes of geographic origin based on region-of-origin model II—eastern USA, western USA, south-of-the USA in Mexico, and north-of-the USA in Canada.

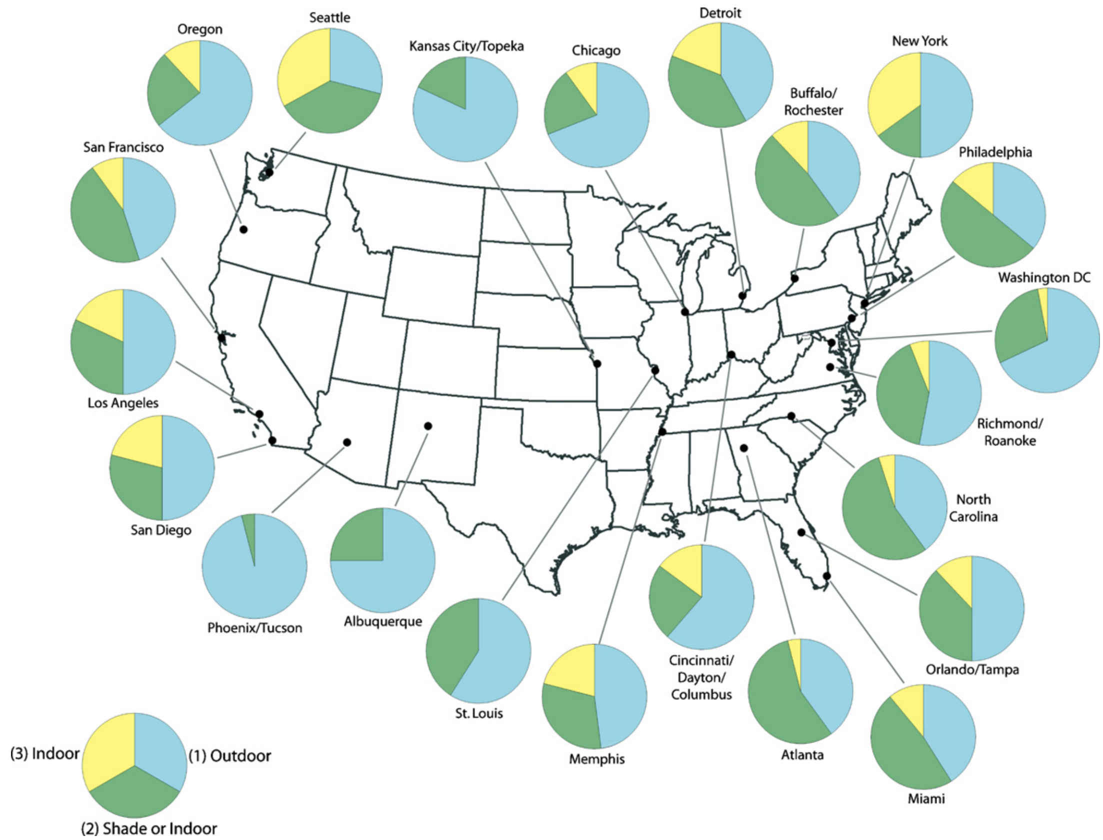

Fig. 4. Proportions of cannabis from 22 consolidated retail areas assigned to one of three classes of cultivation conditions—outdoor, shade or indoor, and indoor.

Discussion

International and interstate trafficking

Both region-of-origin models suggest that foreign-grown cannabis penetrates all areas of the country. To simplify our discussion here we will identify model-predicted origins north-of-the conterminous USA northern border as "Canadian-grown," although Alaska origins are also possible and model-predicted origins south-of-the conterminous USA southern border as "Mexican-grown," although origins from other areas at similar or lower latitudes are possible. Canadian-grown cannabis is not predicted to be limited to northern cities. Likewise, Mexican-grown cannabis is not predicted to be limited to southwestern USA cities. The models predict that cannabis specimens seized in Atlanta, an interior city in the southeast, exhibited significant proportions of Canadian-derived and out-of-region-derived cannabis. This prediction is consistent with conclusions of the National Drug Intelligence Center [NDIC] that identify Atlanta as a national-level drug distribution center (NDIC, 2007).

Even though region-of-origin Model I de-emphasizes cross-border trafficking (see Hurley et al., in press), it still predicted that cannabis seized in border cities would be comprised of a significant portion of foreign-derived seizures. These model predictions support anticipated patterns. Detroit showed the highest proportion of seizures with north-of-the-border isotope ratio signatures, while cannabis seized in Miami contained a high proportion of seizures predicted to originate from south-of-the-border. From a distribution and trafficking perspective, the model predicts that New York City and Miami were the only urban markets showing cannabis derived from both north- and south-of-the-border regions. Based on Model I, only four of 22 metropolitan areas (Kansas City/Topeka, St. Louis, Richmond/Roanoke, and Philadelphia) contained no foreign-derived cannabis seizures. Other interior and mid-Atlantic areas (Albuquerque, Atlanta, and Orlando/Tampa) were predicted to have less than a quarter of seized cannabis originating from within the region, suggesting that these areas have more diversified markets in terms of geographic sources of cannabis. On the other hand, trafficking may be largely local in the northwestern USA (Seattle and Oregon retail areas) where a remarkable 71% of cannabis is predicted to have originated within region. We suggest that patterns such as these are useful for providing understanding of the markets when the seizures occurred and that targeted monitoring programs could track changes in the market in response to a variety of factors, including changes in laws, law enforcement, and other variables.

Based on region-of-origin Model II, there was a tendency for western USA cities to show significant proportions of seized cannabis originating from Mexico, with Los Angeles being a surprising exception. The 28 Los Angeles specimens analysed in this study, were seized over a limited period in Winter 2007 (a few days), whereas specimens from other western cities were seized over a much broader time period. The limited Los Angeles specimens may therefore not represent an adequate sampling of that large market. It is also important to note that for cannabis seized in the eastern USA, Model II cannot reliably distinguish between Mexican-grown cannabis and cannabis grown in some eastern USA regions (Hurley et al., in press). It is possible that Mexican-grown cannabis did penetrate eastern USA markets during the time period of these seizures to an extent that Model II cannot quantify. The model predictions of deep penetration of Canadian-grown cannabis into the south and east coast cities were unexpected. Of all 22 consolidated retail areas analysed, the only area predicted not to have any Canadian-derived seizures was Albuquerque.

Should the recent trends noted by law enforcement agencies continue, it is expected that more interstate trafficking of cannabis will occur as growers continue to expand into states not previously home to large cannabis cultivation operations. Indeed both region-of-origin models indicated significant interstate trafficking of both domestic and foreign-grown cannabis throughout the country. Both models predicted that all but one of the retail areas (Oregon) had 25% or more of the cannabis seizures originating from outside of the seizure region, with even interior metropolitan areas such as Memphis, southwestern Ohio, and Atlanta predicted to have significant proportions of foreign-derived cannabis.

Trends in indoor versus outdoor-growth regimes

Growing cannabis indoors is one straightforward means of hiding the crop from visual aerial surveillance. About 11% of all retail seizures analysed in this study showed clear indoor-growth signals. Another 32% showed indoor or shade-grown signals, indicating that between 11% and 43% of cannabis marketed in the USA is indoor-grown. Generally, northern cities were represented by more indoor-grown cannabis specimens. Of the 71 seizures showing clear indoor-growth signatures ($\delta^{13}C < -32‰$), 60% of them also showed isotope-ratio signatures indicating growth in cooler, more northerly growth climates ($\delta^{2}H < -131‰$). Conversely, 40% of these cannabis seizures with indoor signals also showed isotope ratio values indicating a growth origin in warmer climates, suggesting that significant indoor cultivation operations are occurring in warmer areas as well as more northerly cooler areas. Together these results are consistent with the notion that that indoor-grown cannabis is widely marketed and even produced beyond the expected northern cities in the USA.

Perhaps because we analysed only winter seizures from the Los Angeles region, it might be expected that there would be a higher incidence of indoor-grown cannabis there. However, cannabis specimens exhibiting indoor-grown isotope ratios at other times of the year were also seized from other warm-climate markets (e.g., San Diego, Miami and the Orlando/Tampa areas). In addition, some temperate areas in the Midwest showed very little or no indoor-grown cannabis, including the Kansas City/Topeka and St. Louis areas. Other areas close to Mexico (the Albuquerque and Phoenix/Tucson areas) also showed little or no indoor-grown cannabis.

Previous analysis of northern border seizures by Ehleringer et al. (2007, 2008a,b) showed large proportions of indoor-grown cannabis, whereas southwest border seizures showed little or no indoor-grown cannabis (Ehleringer et al., 2008a, 2008b). These results suggest that Mexican-grown cannabis is largely cultivated outdoors and joint Mexican-American eradication efforts that target elimination of field-grown crops are likely targeted at the bulk of cultivation there. On the other hand, the NDIC has suggested that a significant shift from outdoor to indoor cultivation in Mexico may be occurring, as Mexican drug trafficking organizations take advantage of the higher profit margins possible from indoor operations (NDIC, 2007). Carbon isotope ratio analysis of southwestern border seizures would be a clear indicator of any such shift toward indoor production in Mexico, and thus continued analysis of additional border seizures will be important for evaluating time-dependent trends in cannabis cultivation.

Policy implications

Since the early years of the USA War on Drugs in the 1970s, traffickers have consistently responded to government enforcement activities by shifting operations to avoid detection and minimize seizures while capitalizing on market demands for cannabis of higher potency and purity (e.g., indoor production to avoid aerial detection and to increase potency, and avoidance of Mexican-grown paraquat-laced cannabis in the 1980s by moving production into the USA). The NDIC (2007) recently concluded that indoor production of cannabis continues to increase as growers attempt to avoid outdoor eradication efforts and attain higher profits through production of high-potency cannabis. Furthermore, the NDIC asserted that drug trafficking groups are expanding operations throughout the country to avoid heightened law enforcement pressure in traditionally high production and trafficking states, as well as to avoid higher scrutiny at USA border crossings. Similarly, the NDIC (2007) noted that Mexican drug traffickers have relocated cultivation operations within Mexico 'from traditional growing areas to more remote locations in central and northern Mexico, primarily to reduce the risk of eradication and gain more direct access to U.S. drug markets' (p. 13). Our work here demonstrates that continued stable isotope ratio analysis of seized cannabis throughout the country offers a means to evaluate and track these trends, especially providing information at the retail level that would otherwise be difficult or impossible to obtain at a regional to national scale.

Clear regional patterns and differences in drug trafficking are evidenced in these stable isotope ratio data. The results offer important, independent corroboration for national intelligence estimates of drug trafficking. The continued development and enhancement of the stable isotope ratio toolset will help enhance and expand its applicability to this critical international issue. Specifically, our results illustrate that new insights can be obtained from stable isotope ratio analyses relevant to policy-related questions on geographic origin and growth environments of seized cannabis, including evaluating the effectiveness of cannabis crop reduction strategies, and tracking changes in cannabis distribution routes and regional production and trafficking trends.

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