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The Stable Isotope Ratios of Marijuana. II. Strontium Isotopes Relate to Geographic Origin

ABSTRACT: Effectively addressing marijuana trade is aided by understanding marijuana geographic sources. We analyzed the $^{87}Sr/^{86}Sr$ of marijuana samples grown in 79 counties across the United States to determine if a primary geologic signal is retained in marijuana, which could therefore be useful for geographic sourcing. The marijuana results were compared with modeled bedrock $^{87}Sr/^{86}Sr$ values based on ^{87}Rb decay rates and a generalized geologic map of the U.S.A. A significant correlation was observed between marijuana $^{87}Sr/^{86}Sr$ and modeled bedrock $^{87}Sr/^{86}Sr$. Although values clustered near the 1:1 relationship, there was a predominance of positive anomalies, perhaps attributable to carbonate bedrock. A small number of negative anomalies were also observed, which were generally associated with granitic bedrocks. These results suggest that strontium isotopes in marijuana record the geographic origins of marijuana, and that refinement of the base strontium map (or strontium isoscape) and improved understanding of other strontium sources would be productive.

KEYWORDS: forensic science, stable isotope ratio, heavy isotopes, drug intelligence, *Cannabis sativa*, thermal ionization mass spectrometry, sourcing

In order to determine if a primary geologic signal is retained in marijuana strontium isotope ratios that would allow strontium to be used for geographic sourcing, we analyzed the $^{87}Sr/^{86}Sr$ of marijuana samples grown in 79 different counties across the United States using thermal ionization mass spectrometry (TIMS). These results were compared with modeled bedrock $^{87}Sr/^{86}Sr$ values based on rubidium decay rates and a generalized geologic map provided by the United States Geological Survey (USGS).

Marijuana (*Cannabis sativa* L.) is the most widely used illicit drug in the United States (1–4) and is associated with a range of public health concerns (5–12). Effectively addressing illicit trade in marijuana is aided by an understanding of its cultivation practices and distribution routes, thereby contributing to useful forensic drug intelligence (13). However, the current understanding of geographic sources and movements of marijuana remains relatively poor. Stable isotope ratios, chemical compositions, and genetic approaches have all been applied to the identification of geographic sources and cultivation methods of marijuana (14–23). Because stable isotope ratios of plant tissues can "record" aspects of a plant's growth environment (24), stable isotopes have a unique potential to yield information on geographic origin and cultivation of seized samples that other methods would not yield. Previous work has shown the potential utility of light stable isotope ratios in this area (19–21,25–27). The specific application of carbon and nitrogen isotope ratios to marijuana cultivation practices are discussed elsewhere (28).

In addition to the potential geographic signals that can be detected in the light stable isotope ratios of marijuana, spatial variation in the heavy isotopes has a clear potential to provide independent geographic, soil-based source information. Variation in the Sr isotope ratios of biological materials ($^{87}Sr/^{86}Sr$) has been explored for a variety of archaeological and other applications for understanding geographic sources or movement of materials (29–34). However, it has not been explored for applications related to the geographic sourcing of marijuana.

Strontium isotope ratios vary spatially, with this variation largely dependent on soil mineralogy (specifically the time since crystallization and Rb content); however, atmospheric deposition, complex soil-forming processes, and fertilizer inputs all have the potential to obscure the expected geographic signal (31,35). An important evaluation of the potential utility of strontium isotopes for geographic sourcing of marijuana is to evaluate the observed variation in marijuana strontium isotopes across a wide range of bedrock ages to assess whether this fundamental geological "signal" is retained in marijuana tissues, or if other strontium inputs are large enough to mask the bedrock signal. It is important to note here that even if this geological signal is obscured by other sources, strontium isotope ratios could still be used to identify source regions. In these cases, it must be established that those source regions had different and consistent strontium isotope ratios, a significant investment of effort. A finding that the underlying bedrock imparts a signal to marijuana simplifies the interpretation of these measurements and will provide increased confidence in establishing *a priori* expectations prior to intensive sampling efforts. We report here the results of a survey of marijuana $^{87}Sr/^{86}Sr$ from plants cultivated within the conterminous states of the U.S.A. These results were compared with a

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simplified strontium isoscape (modeled spatial distribution of bedrock $^{87}Sr/^{86}Sr$ based on bedrock age; [36]) and the implications for forensic applications are discussed.

Strontium is chemically similar to calcium (similar charge and ionic radius) and substitutes for Ca in physical and biological systems. Sr has been utilized to understand such processes as rock weathering and Ca dynamics in plant–soil systems (e.g., 31,38,39). ^{87}Sr is radiogenic, forming as a beta decay product of ^{87}Rb. ^{87}Rb has a long half-life of 4.88×10^{10} years (39), resulting in a wide range of abundances of ^{87}Sr in Earth's minerals. All other stable isotopes of strontium are nonradiogenic (^{88}Sr, ^{86}Sr, and ^{84}Sr) and because the abundance of ^{86}Sr is similar to that of ^{87}Sr, the stable strontium isotope ratios of materials are reported as $(^{87}Sr/^{86}Sr)_{\text{measured}}$, or often with reference to a "bulk earth" $(^{87}Sr/^{86}Sr)_{\text{bulk earth}}$ value of 0.7045 as $\varepsilon^{87}Sr$:

$$\varepsilon^{87}\mathrm{Sr} = \left(\frac{\left(\frac{^{87}\mathrm{Sr}}{^{86}\mathrm{Sr}}\right)_{\text{measured}}}{\left(\frac{^{87}\mathrm{Sr}}{^{86}\mathrm{Sr}}\right)_{\text{bulkearth}}} - 1 \right) * 10000 \qquad (1)$$

Based on the ratio of Rb to Sr, the initial $^{87}Sr/^{86}Sr$ of the rock, and time since crystallization, the modern strontium isotope ratio of any rock sample can be described by the following equation:

$$\left(\frac{^{87}\mathrm{Sr}}{^{86}\mathrm{Sr}}\right)_P = \left(\frac{^{87}\mathrm{Sr}}{^{86}\mathrm{Sr}}\right)_I + \left(\frac{^{87}\mathrm{Rb}}{^{86}\mathrm{Sr}}\right)(e^{\lambda t} - 1) \qquad (2)$$

where the subscripts P and I refer to the sample at the present time and at some time in the geologic past respectively (e.g., the time of crystallization of volcanic rock; [36]), t refers to time (years), and λ is the decay constant (per year; 1.42×10^{-11} for the above half-life; see also [40]). To a first approximation, then, bedrock $^{87}Sr/^{86}Sr$ can be predicted from rock age and some estimate of Rb and Sr concentrations in the rock (36). There is not likely to be significant isotopic fractionation with uptake given the small relative mass difference between ^{87}Sr and ^{86}Sr, thus plant $^{87}Sr/^{86}Sr$ should reflect the $^{87}Sr/^{86}Sr$ of the "available" strontium in soils (41). This pool of strontium is potentially different from that of the bulk parent material due to atmospheric deposition, cycling of strontium by plants, weathering effects, and other events that transport materials across Earth's surface (30,37,42). The direction or degree of divergence, however, is not known at large scales, nor is the geographic patterning of any divergence. Large-scale surveys of plant strontium isotope ratios can elucidate first-order relationships and potential geographically based offsets from simple expectations.

We report here the results of a survey of $^{87}Sr/^{86}Sr$ from marijuana samples known to have been cultivated in 79 different counties across the United States and selected specifically to maximize geologic variability within the limits of sample availability from the University of Mississippi Marijuana Potency Project. This is the first survey of its kind for marijuana and provides a first-order evaluation of the ability of strontium isotope ratios to record region-of-origin for seized marijuana specimens.

Methods

We analyzed domestic, outdoor-grown marijuana samples for strontium isotope ratios ($^{87}Sr/^{86}Sr$) by TIMS. We obtained 93

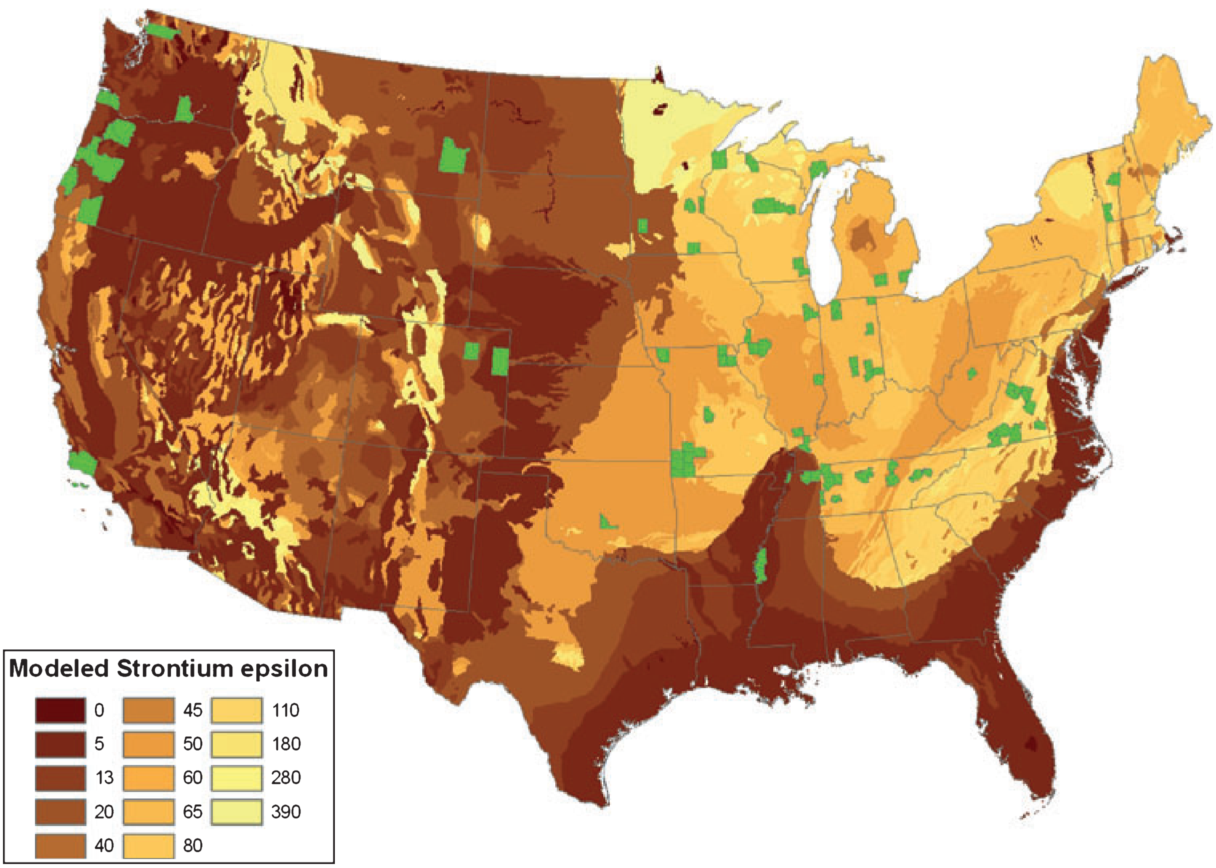

FIG. 1—*Predicted strontium isotope variations (epsilon scale; see text for definition) of the conterminous United States based on a bedrock age model described by Beard and Johnson (36) and rock ages described by Vitoria et al. (42).*

samples of known county origin that had been seized by the Drug Enforcement Administration (DEA) in 2003 and 2004. The samples were selected to represent a wide range of expected strontium isotope ratios (see Fig. 1). For samples from which leaf material could be isolated, we analyzed leaf-only fractions (n = 64). Inflorescence fractions of five samples were also analyzed to allow comparisons with leaves. In cases where it was not possible to clearly distinguish leaf and inflorescence fractions, we analyzed a mixture of leaf and inflorescence material (n = 29). We pulverized dried sample fractions with mortar and pestle, filtering residual large particles by passing ground material through 250 μm stainless steel sieves. In preparation for TIMS, we placed 0.3 to 0.9 g of pulverized sample material into acid-washed quartz crucibles and dried the samples for 2 h at 80°C in a muffle furnace. The temperature in the muffle furnace was increased to 200°C for an additional 2 h, then to 600°C, allowing the samples to combust overnight.

Ashed samples were treated with 1 mL of 7 M nitric acid at 80°C, allowing reflux in the quartz crucibles for 1 h, to extract strontium from the ash material. The solution was transferred to 15 mL Teflon beakers and then evaporated. The residue was reacted with 1 mL of concentrated nitric acid at 80°C, and the acid was allowed to evaporate; this nitric acid step was repeated. The remaining solid was suspended in 0.25 mL concentrated nitric acid, then reacted with three aliquots of 0.1 mL 30% hydrogen peroxide at 80°C to eliminate all organics from the sample. After the samples were dried down, they were dissolved in 0.5 mL 3.5 M nitric acid. This solution was processed through 50 μL cation exchange columns containing strontium exchange resin (Eichrom Sr-Spec; [43]). Purified samples were dried with a drop of 0.15 M H_3PO_4. Dried samples were resuspended in a mixed $TaCl_5$–H_3PO_4 solution. Finally, samples were loaded on degassed rhenium (Re) filaments for analysis by TIMS (GV IsoProbe-T; IsotopX, Middlewich, Cheshire, U.K.) using a 3-cycle dynamic multicollection routine with a target intensity of 3 V ^{88}Sr. Total procedure blanks were insignificant compared with sample sizes (>1 μg Sr). All analyses were fractionation corrected to ^{86}Sr/^{88}Sr = 0.1194 and data were reported with respect to a ^{87}Sr/^{86}Sr value of 0.710250 for the strontium carbonate isotopic standard (NIST SRM 987). During the period of these analyses, the measured ^{87}Sr/^{86}Sr value of SRM 987 averaged to 0.710240 ± 0.000014 (2σ, n = 61).

The measured marijuana ε^{87}Sr values were compared with those expected from the bedrock ages based on data from the USGS Generalized Geologic Map of the United States (44). Using geographic information system (GIS) intersection tools, each map unit that fell within a given county was assigned a ε^{87}Sr value based on equation 2 (36). One county in the database encompassed seven unique geologic units, but this was an extreme exception, as over half of the counties included no more than two total units and over 75% no more than three. For each county, the median ε^{87}Sr value was taken as the mid-point between the maximum and minimum values based on the bedrock within the county. These median values were then compared with the measured marijuana ε^{87}Sr values.

For two states, Oregon and Tennessee, published ^{87}Sr/^{86}Sr soil and rock data were also compiled. Although, as with the Beard and Johnson model predictions (36), these data did not directly represent plant-available strontium, they did represent local measured values and allowed an additional first-order comparison for the marijuana strontium data.

Results and Discussion

The strontium isotope ratios of the 93 marijuana samples ranged from 0.70410 to 0.71995 (ε^{87}Sr = −6 to 219), similar to the range expected based on the ages of the underlying geology across the regions sampled (see Fig. 1). Two separate extractions and measurements of the same ground marijuana sample exhibited high precision (2σ = ±0.00001 for each and differing by a value of <0.00001). As expected, there was no significant difference between leaf and flower strontium isotope ratios based on a paired t-test (n = 5, p = 0.9425) and these were highly correlated (R = 0.998; p < 0.005) with an absolute mean difference of <0.00001.

Measured marijuana ε^{87}Sr was significantly correlated with the county median expected ε^{87}Sr from bedrock age (R = 0.49, p < 0.001, n = 93; see Fig. 2). The average offset across counties from the median predicted value was +22, with some significantly larger values and some exceeding the maximum ε^{87}Sr value expected from the bedrock found within the source county. The median range in within-county predicted ε^{87}Sr was 20, although a few counties had high ranges reflecting their complex geologies (maximum range in expected ε^{87}Sr values = 250; see Table 1). Four different samples from one county in Illinois with different seizure dates in 2004 had, at the scale of variation across the U.S.A., similar ε^{87}Sr values, ranging from 71 to 88, suggesting that if accurate local strontium isotope ratios could be established, the strontium isotope ratios of plants grown in a given location would show high fidelity from year to year. It is important to note, however, that this range of variation is much larger than analytical uncertainty, suggesting either the presence of significant local spatial variation in source strontium isotope ratios, or perhaps seasonal differences in plant-available strontium isotope ratios.

Two primary conclusions can be drawn from these results. First, the strontium isotope ratios of marijuana recorded a local, geologically based signal. This observation is consistent with previous

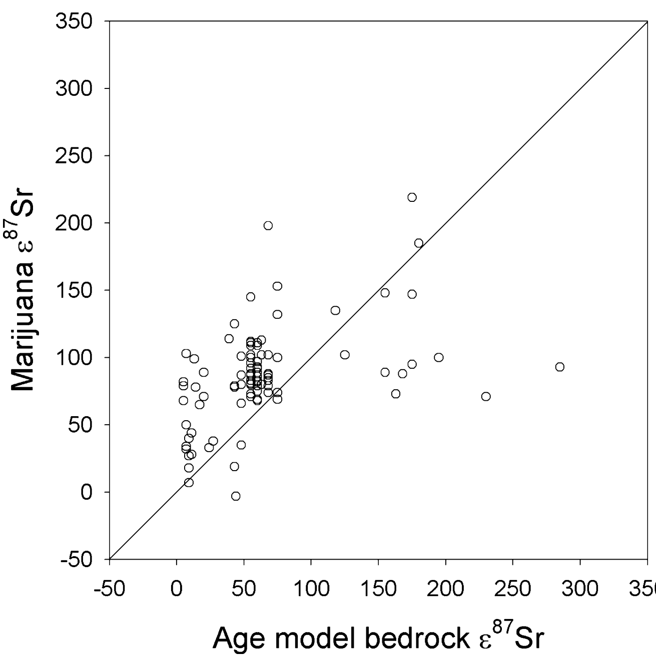

FIG. 2—*Measured marijuana ε^{87}Sr versus median modeled bedrock ε^{87}Sr for the source counties. The diagonal line indicates the 1:1 relationship. All marijuana samples were obtained from leaves or a mixture of leaf and inflorescence material from known counties-of-origin. The spatial distribution included nearly the full range of expected variation in strontium isotope ratios in the conterminous U.S.A. Many of the data points with large positive excursions are from carbonate-rich regions, whereas many of those with large negative excursions are from granite-rich regions (see text for details).*

TABLE 1—*Complete list of measured marijuana strontium isotope ratios, and the predicted minimum and maximum bedrock $\varepsilon^{87}Sr$ values for the respective counties.*

County	State	Marijuana $^{87}Sr/^{86}Sr$	Marijuana Epsilon	Bedrock Median	Bedrock Minimum	Bedrock Maximum
Santa Barbara	CA	0.70681	33	24	8	40
Morgan	CO	0.71077	89	20	20	20
Yuma	CO	0.71001	78	14	8	20
Hawaii	HI	0.70800	50	7	5	8
Maui	HI	0.70677	32	7	5	8
Maui	HI	0.70688	34	7	5	8
Clark	IL	0.71016	80	48	45	50
Fulton	IL	0.71018	81	55	45	65
Fulton	IL	0.71012	80	55	45	65
Fulton	IL	0.70953	71	55	45	65
Fulton	IL	0.70952	71	55	45	65
Fulton	IL	0.71072	88	55	45	65
Henderson	IL	0.70967	73	55	45	65
Massac	IL	0.71009	79	43	20	65
McDonough	IL	0.71065	87	55	45	65
Pope	IL	0.71002	78	43	20	65
Will	IL	0.71170	102	63	45	80
Williamson	IL	0.71060	87	48	45	50
Decatur	IN	0.71074	89	60	55	65
Franklin	IN	0.71008	79	68	55	80
Johnson	IN	0.70939	69	60	55	65
Laporte	IN	0.71008	79	60	55	65
Marion	IN	0.70975	75	60	55	65
Rush	IN	0.70973	74	68	55	80
Starke	IN	0.71027	82	60	55	65
Steuben	IN	0.70936	69	60	55	65
Wells	IN	0.71037	83	60	55	65
Delta	MI	0.71171	102	68	55	80
Jackson	MI	0.71038	83	55	45	65
Schoolcraft	MI	0.71847	198	68	55	80
Wayne	MI	0.70929	68	60	55	65
Freeborn	MN	0.71033	83	68	55	80
Hennepin	MN	0.70939	69	75	70	80
Lyon	MN	0.70947	71	20	20	20
Washington	MN	0.70969	74	75	70	80
Barry	MO	0.71243	113	63	45	80
Dade	MO	0.71155	100	55	45	65
Greene	MO	0.71012	80	63	45	80
Jasper	MO	0.71123	96	55	45	65
Knox	MO	0.71167	102	55	45	65
Lawrence	MO	0.71128	96	55	45	65
Lewis	MO	0.71102	92	60	55	65
McDonald	MO	0.71221	109	55	45	65
Morgan	MO	0.71048	85	68	55	80
Newton	MO	0.71242	112	55	45	65
Nodaway	MO	0.70918	66	48	45	50
Scotland	MO	0.71098	92	55	45	65
Bolivar	MS	0.70931	68	5	5	5
Washington	MS	0.71005	79	5	5	5
Custer	MT	0.70906	65	17	13	20
McClain	OK	0.71162	101	48	45	50
Benton	OR	0.70496	7	9	5	13
Clackamas	OR	0.70643	27	9	5	13
Clatsop	OR	0.70763	44	11	8	13
Columbia	OR	0.70651	28	11	8	13
Coos	OR	0.70714	38	27	13	40
Jackson	OR	0.70428	−3	44	8	80
Lane	OR	0.70732	40	9	5	13
Marion	OR	0.70576	18	9	5	13
Cumberland	TN	0.71473	145	55	45	65
Decatur	TN	0.71328	125	43	20	65
Dickson	TN	0.71135	97	60	55	65
Fentress	TN	0.71235	111	55	45	65
Henry	TN	0.71253	114	39	13	65
Houston	TN	0.71054	86	60	55	65
Humphreys	TN	0.71232	111	60	55	65
Jefferson	TN	0.71379	132	75	70	80
Knox	TN	0.71529	153	75	70	80
Lake	TN	0.71025	82	5	5	5
Lewis	TN	0.71221	109	60	55	65

TABLE 1—*(Continued).*

County	State	Marijuana $^{87}Sr/^{86}Sr$	Marijuana Epsilon	Bedrock Median	Bedrock Minimum	Bedrock Maximum
Smith	TN	0.71073	88	68	55	80
Stewart	TN	0.71106	93	60	55	65
Weakly	TN	0.71146	99	13	13	13
Wilson	TN	0.71156	100	75	70	80
Albemarle	VA	0.71120	95	175	70	280
Augusta	VA	0.71403	135	118	55	180
Buckingham	VA	0.71492	148	155	30	280
Floyd	VA	0.71995	219	175	70	280
Franklin	VA	0.71487	147	175	70	280
Lunenburg	VA	0.70966	73	163	45	280
Patrick	VA	0.71155	100	195	110	280
Pittsylvania	VA	0.71080	89	155	30	280
Bennington	VT	0.71994	219	175	70	280
Orange	VT	0.71068	88	168	55	280
Benton	WA	0.71178	103	7	5	8
Skagit	WA	0.70582	19	43	5	80
Douglas	WI	0.71753	185	180	180	180
Iron	WI	0.71107	93	285	180	390
Marathon	WI	0.70950	71	230	180	280
Racine	WI	0.71072	88	68	55	80
Shawano	WI	0.71170	102	125	70	180
Waukesha	WI	0.71064	87	68	55	80
Gilmer	WV	0.70695	35	48	45	50

These states were selected for their relatively large sample sizes and distinct distributions of measured $^{87}Sr/^{86}Sr$ values. Sources for the published $^{87}Sr/^{86}Sr$ values are listed in Appendix 1.

evidence that plant-available strontium should primarily reflect the dominant, underlying geology, with inputs from other sources having second-order effects (35), encouraging the further development of strontium isotopes as a tool for geographic sourcing of seized marijuana specimens. Not surprisingly, there remained considerable variation in the observed marijuana strontium isotope ratios that could not be explained based on simple correlations with predictions based on the underlying bedrock at the scale of individual counties. Approximately 80% of samples had measured values that fell outside the bounds of predicted $\varepsilon^{87}Sr$ for their county-of-origin. Most of these divergences were positive anomalies, suggesting either that the age-based bedrock model underpredicts true bedrock $\varepsilon^{87}Sr$ values, or that there was consistently a second, important strontium source in plant-available strontium that was more radiogenic than the underlying bedrock.

Although our survey did not include detailed analyses of the range of potential sources of strontium to plants in the 79 counties sampled, four classes of potential explanations may be established for our observations. These were (i) variations in the bedrock not explained by the bedrock age model, (ii) bulk soil strontium sources that differed from the underlying bedrock, (iii) internal cycling of strontium or other biological processes that resulted in the plant-available strontium isotope ratios differing from bulk soils, and (iv) significant inputs from outside sources such as atmospheric deposition or fertilizers.

Differential weathering of parent materials could result in divergence between bedrock strontium isotope ratios and that of the soils in which plants grow. Although clearly increases or decreases in soil $^{87}Sr/^{86}Sr$ are possible with differential weathering, depending on rock mineral composition, for soils formed on carbonate bedrocks, soil strontium isotope ratios could be consistently higher than the underlying bedrock formations. This would occur through the preferential losses of carbonate materials, leaving soils disproportionately composed of more slowly weathering silicate materials with higher Rb/Sr and $^{87}Sr/^{86}Sr$ ratios (e.g., [45]). It is possible that the large number of samples exhibiting positive offsets from age-model expectations could be due to weathering of carbonate parent materials. Although not intentional, many of our samples were from regions with large carbonate deposits such as regions in the midwest and along the Appalachian mountain range (46,47). This could contribute to the generally positive offset observed in the dataset. It would be useful in future work to sample plants growing in regions such as North Dakota, northern Minnesota, or the coastal plains of Texas to evaluate whether those locations yielded better agreement between plant $^{87}Sr/^{86}Sr$ values and the age model expectations. Of the 13 samples (Fig. 2) falling below

TABLE 2—*Comparison with published $^{87}Sr/^{86}Sr$ values for soils or rocks from within sample county-of-origin for Oregon and Tennessee for those sample counties with published data.*

County	Measured Marijuana $^{87}Sr/^{86}Sr$	Minimum Published $^{87}Sr/^{86}Sr$	Maximum Published $^{87}Sr/^{86}Sr$	Geologic Province	n
Oregon					
Benton	0.70496	0.70300	0.71262	Coast Range	27
Clackamas	0.70643*	0.70285	0.70617	High Cascades	219
Clatsop	0.70763	0.70300	0.71262	Coast Range	27
Columbia	0.70651	0.70300	0.71262	Coast Range	27
Coos	0.70714	0.70300	0.71262	Coast Range	27
		0.70307	0.71760	Klamath	76
Jackson	0.70428	0.70307	0.71760	Klamath	76
		0.70285	0.70617	High Cascades	219
Lane	0.70732	0.70300	0.71262	Coast Range	27
		0.70320	0.70390	West Cascades	5
		0.70285	0.70617	High Cascades	219
Marion	0.70576	0.70320	0.70390	West Cascades	5
		0.70285	0.70617	High Cascades	219
Tennessee					
Jefferson	0.71379	0.70809	1.095	Valley and Ridge	131
Knox	0.71529	0.70809	1.095	Valley and Ridge	131
Smith	0.71073	0.70794	0.7109	Central Basin	25
Wilson	0.71156*	0.70794	0.7109	Central Basin	6

*Measured marijuana values outside the range of reported literature values.

the 1:1 line by greater than 10 epsilon units, 12 originated in counties from five states (OR, VA, VT, WA, and WI) identified as containing granitic rocks or gneiss. Our results therefore strongly suggest that plant-available strontium in soils on these formations is consistently nonradiogenic relative to expectations from the bedrock age model, and consistent with expectations based on weathering of less radiogenic components of these rocks (48).

In addition to the age-only bedrock model discussed here, Beard & Johnson (36) described a model for predicting mineral strontium isotope ratios that yielded strontium concentration-weighted estimates of ε^{87}Sr. That model depended on measurements of the strontium concentration and isotope ratios of local soil and bedrock samples and accounted for the varying contributions of these materials to an expected concentration-weighted local pool. Unfortunately data on local strontium concentrations were not available for this study, thus the concentration-weighted model could not be directly applied. However, if these concentration-weighted strontium isotope ratio values consistently yielded higher local means than did the simple median calculated here, this could explain part of the generally positive offsets observed in the marijuana ε^{87}Sr values. We do not think this is likely because many rocks with high strontium isotope ratios also have low strontium concentrations, which will result in a decrease of the expected ε^{87}Sr values of the underlying bedrock, an effect that will generally worsen the agreement between rock and plant ε^{87}Sr in our dataset (35).

Several other potential sources of strontium to plants could explain variability in our dataset. If, as expected, many of these plants were receiving fertilizer addition (28), this would affect their strontium isotope ratios. Based on a recent survey of fertilizer isotope ratios, the ^{87}Sr/^{86}Sr of fertilizers can range from 0.703 to a very radiogenic value of 0.835 from a KCl fertilizer that probably contained very high concentrations of Rb and therefore high

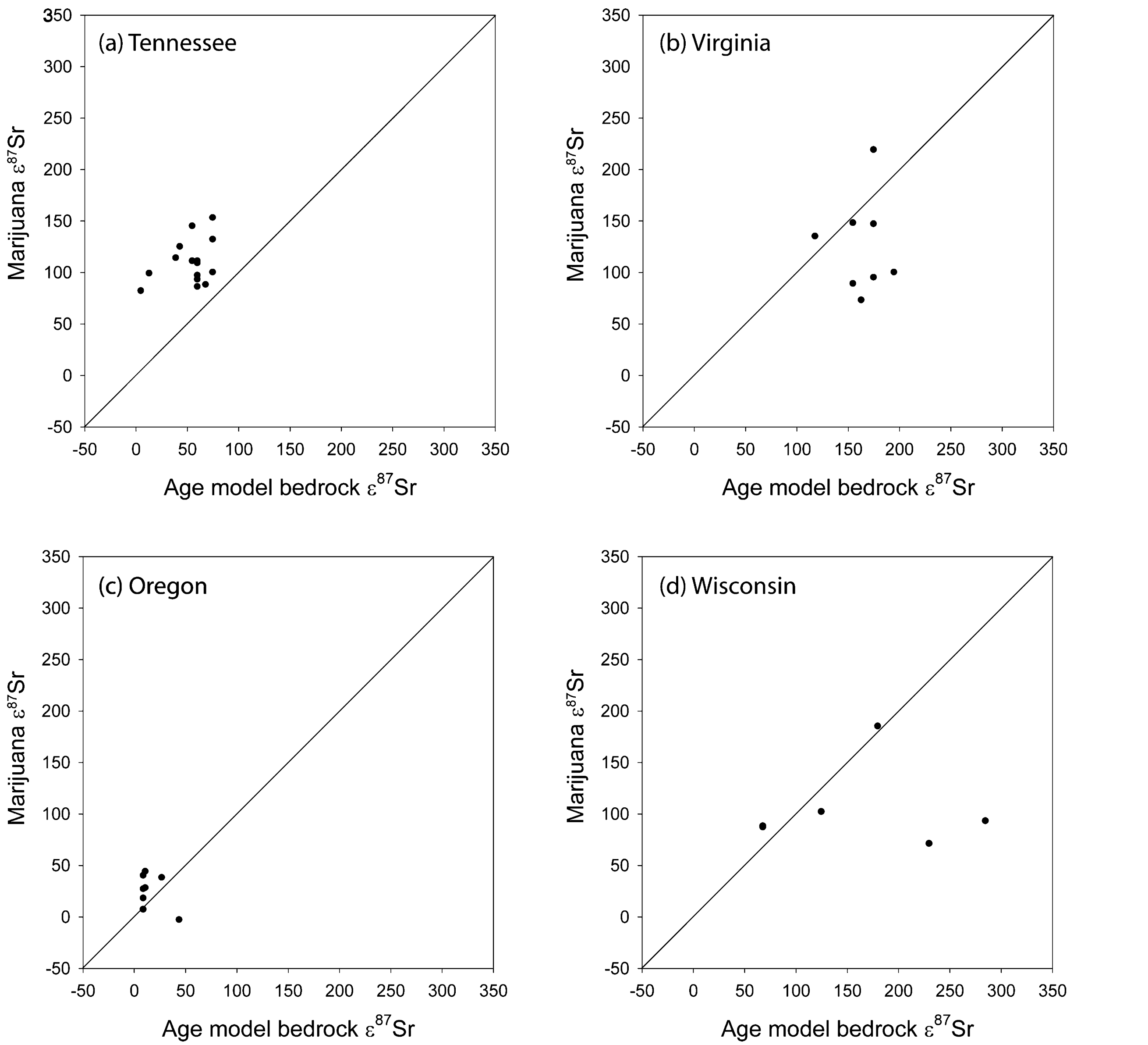

FIG. 3—*Measured marijuana ε^{87}Sr versus median modeled bedrock ε^{87}Sr for the source county (see Fig. 1) for Tennessee (a), Virginia (b), Oregon (c), and Wisconsin (d).* All marijuana samples were obtained from leaves or a mixture of leaf and inflorescence material from known counties-of-origin (leaves and inflorescences were not significantly different from each other). States are shown to represent the range of observed values and patterns with respect to bedrock, with the full dataset available in Table 1.

amounts of ^{87}Sr (ε^{87}Sr of −21 to 1852). Vitória et al. (42) pointed out that the fertilizers observed to have high ^{87}Sr/^{86}Sr were those with high concentrations of potassium. More detailed work on strontium sources to marijuana growing in particular regions could yield interesting insights into not only the potential for strontium isotopes to geographically source plants, but also into the cultivation practices of growers. In addition, near-shore aerosols and particulates derived from the oceans could influence plant-available strontium (49). We did not see strong evidence of this in the samples collected in coastal counties. For example, although Benton and Coos counties in Oregon had values lower than the age model predicted and therefore could have had an oceanic influence, their values were also within the range of published literature values for the Coast Range (see Table 2). It is important to note that many counties cover a relatively large area and it is not known where within a given county the sample grew, making influences like ocean aerosols difficult to evaluate.

As with all applications of strontium isotope ratios to geographic source inferences, detailed understandings of the isotope ratios of plant-available Sr in potential source regions will yield the greatest power in identifying likely source regions for samples of unknown origin (e.g., [31, 36, 50]). At a national scale, it is clear from our results that many regions will be indistinguishable based on strontium isotope ratios without additional detailed information, even when the underlying bedrock is expected to differ significantly. However, in other cases where the expected bedrock ε^{87}Sr values differ by relatively large amounts (e.g., samples grown in Oregon to those grown in Virginia or Wisconsin where observed differences are larger than *c.* 50 epsilon units; see [Fig. 3]), it may not be unreasonable to utilize strontium isotope ratios alone to address specific questions such as whether a particular specimen originated in one of two locations.

We concluded that although considerable unexplained variability remained, marijuana strontium isotope ratios did retain a primary geologic signal based on bedrock age. These results suggest that strontium isotopes in marijuana have significant promise for application to geographic sourcing. The utility to specific forensic questions will be improved through finer-scale sampling of plants and soils, thus establishing local signatures prior to an application to unknowns. Also, common origins could be inferred from similar strontium isotope ratios, even lacking additional local information, if the range of possible origins could be constrained such that a unique isotope ratio would be expected for a given location.

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Appendix I

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