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^{14}C analyses quantify time lag between coca leaf harvest and street-level seizure of cocaine

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ABSTRACT

Measurements were made on the natural abundance ^{14}C content (Δ^{14}C) of cocaine specimens seized between 2003 and 2009. The objective of this study was to determine the extent to which Δ^{14}C analyses could quantify the "age" of recent cocaine seizures. Here "age" of a seized cocaine specimen is defined as the time period between when a coca leaf was harvested in South America and its seizure as cocaine at either the international or domestic street levels. Based on Δ^{14}C analyses of seizure specimens, there were no statistically significant differences in the ages of domestic cocaine HCl and cocaine base specimens seized on the streets in different locations across the United States. Between 2007 and 2009, the average age of a street-level cocaine seizure in the United States was 24.6 ± 1.1 months. Cocaine shipment seizures that were in excess of 150 kg during this time period had an average age of 18.2 ± 1.4 months, whereas smaller shipment seizures were significantly older with an average age of 22.3 ± 0.6 months. Analyses of the largest cocaine shipment seizures suggested that these seizures were composed of specimens with different ages, possibly representing accumulations over as much as a 31-month period.

1. Introduction

Cocaine is a widely distributed and highly addictive stimulant, and is categorized in the United States as a Schedule II drug under the Controlled Substances Act of 1970. During the 5-year period 2005–2009, the amount of cocaine seized in the U.S. averaged 76,802 kg [1]. Cocaine is easily obtained on the street in U.S. cities and represents a chronic burden to both health care and law enforcement systems. Over the past two decades the U.S. Drug Enforcement Administration's Cocaine Signature Program (CSP) at its Special Testing Research Laboratory (DEA-STRL) has developed a number of chemical characterization approaches to trace the geographical origins of cocaine [2–7], including stable isotope and chromatographic approaches. However, in contrast to region-of-origin information, little is known from a scientific viewpoint about the age of a cocaine specimen sold on the streets today.

There are no quantitative data on the time lag between coca production and street sales of cocaine. Thus, for years there has been a disconnect between estimates of cocaine production, flow, and consumption, leading U.S. intelligence analysts and policy-makers to assume one or more of the estimates were invalid, or that strategic stockpiles in South America, Mexico, or elsewhere allowed traffickers to manipulate cocaine flow regardless of current production. One of the key pieces connecting production, flow, and consumption – the time lag between production and the retail market – has never been fully understood. Analysts previously assumed a 6–12 month lag, but little reporting existed to support that estimate. Without these data, questions regarding strategic stockpiling and supply reduction effects have been difficult to quantify with confidence.

The ^{14}C content at natural abundance levels has been applied as a quantitative technique to determine the age of modern biological materials (post 1962), because of the atmospheric ^{14}C 'bomb spike' associated with extensive aboveground nuclear testing in advance of the 1963 Nuclear Test Ban Treaty [8,9]. The ^{14}C measurement of modern biological samples has allowed quantitative determination of age for a number of forensic applications [10], including human age determinations through analyses of teeth [11,12], the

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ages of human skeletal remains [13–15], opium and wine year of production [16], and the year that an individual died based on hair analyses [17,18].

Determination of $\Delta^{14}C$ values of cocaine specimens could be used to examine the time lag between coca leaf harvest in the field and when a seized cocaine specimen in transit or on the streets of the United States. Prior to this study, analysts could not demonstrate that an apparent decline in cocaine supply within South America had a measurable strategic impact on cocaine availability in the United States. In this regard, the average time it takes for cocaine to make the journey from a coca leaf harvested to street-level consumption in the United States is not well understood. However, all available information clearly indicated that not all the cocaine produced in a year was actually consumed in that same year. Some analysts have suggested that traffickers may maintain strategic stockpiles of cocaine to compensate for fluctuations in the supply. Although an attractive theory, the intelligence and drug law enforcement communities have no hard information to either prove or disprove the strategic stockpile theory.

The objective of this study was to determine lag times between harvest of coca leaves in the field and the seizure of cocaine within the United States. Although the year-to-year changes in atmospheric ^{14}C are continuously decreasing [8,9], which reduces the time resolution capacity of the modern ^{14}C measurement, with careful calibration we hypothesized that sufficient time resolution was still possible to provide quantitative estimates of the ages of cocaine specimens seized on the streets of the United States.

2. Materials and methods

2.1. Cocaine specimen acquisition

$\Delta^{14}C$ results are reported for 539 cocaine specimens, obtained through the DEA-STRL. We analyzed 423 cocaine HCl and 116 cocaine base specimens. Most cocaine HCl or cocaine base specimens were "street seizures." Others were described as bulk seizures (threshold of >10 kg). The 423 cocaine-HCl specimens represented 307 seizures. Each of the 116 cocaine base specimens analyzed represented a different seizure. Seizure dates for cocaine specimens in this study ranged between October 2003 and June 2009, spanning a $\Delta^{14}C$ range of 119‰ to 38‰, respectively. The Supplementary Material File associated with this publication provides a description of each specimen and its $\Delta^{14}C$ value (‰).

Of the cocaine specimens analyzed, 455 were seized in the continental United States and 12 in U.S. territories, representing 368 and 7 seizures, respectively. An additional 72 specimens were seized outside the United States, representing 48 seizures as described: Australia ($n = 1$), Bolivia ($n = 11$), Brazil ($n = 1$), Colombia ($n = 2$), the Eastern Pacific ($n = 3$), Ecuador ($n = 3$), Israel ($n = 1$), Italy ($n = 18$), Mexico ($n = 1$), Peru ($n = 3$) and Thailand ($n = 4$).

2.2. ^{14}C analyses and reference materials

Determination of $\Delta^{14}C$ contents in cocaine specimens were made on graphite targets produced from CO_2 that resulted from the combustion of the cocaine specimen [19]. Measurements were made on the accelerator mass spectrometer (AMS) at the UC Irvine Keck Carbon Cycle AMS Laboratory (http://www.ess.uci.edu/ams/).

All ^{14}C observations are presented as $\Delta^{14}C$ (‰) values with units of ‰ or per mil deviation from the 1950 standard [8,19]: where x is the measurement year (2009). See also Supplementary Material File.

$$\Delta^{14}C = \left[\frac{\left[{}^{14}C/{}^{12}C\right]_{\text{sample},-25}}{0.95 \cdot \left[{}^{14}C/{}^{12}C\right]_{\text{OX1},-19} \cdot \exp^{(x-1950/8267)}} - 1 \right] \times 1000‰ \quad (1)$$

A series of internal reference materials commonly used in AMS allowed us to independently determine the precision of the analyses and therefore the age resolution of the technique. These reference materials included standards commonly used at the Keck Lab: acetanilide (for use as a blank), oxalic acid (OX2) for data correction, and ANU-sucrose and cellulose (IAEA-C3) as secondary standards. A second oxalic acid reference material (IAEA-C7) was analyzed in several analytical runs (wheels) as an additional quality control measure. Observed variations in the reference material results over the course of our observations are summarized in Table 1. The results show that the radiocarbon dating can resolve differences among any individual specimen that are ≥4.3‰ in $\Delta^{14}C$. In this study, interpretations will be based on the most conservative of the reference material

Table 1
Observed $\Delta^{14}C$ (mean ± 1 standard deviation) values (‰) for reference materials measured throughout the duration of this study.

$\Delta^{14}C$ (‰)	ANU-sucrose	IAEA-C3	IAEA-C7	OX2
Mean	491.4	288.5	−506.8	331.1
±1 standard deviation	2.7	4.3	1.9	2.7
Count	48	24	10	141

precision estimates: IAEA-C3. We therefore calculated radiocarbon analytical precision using the reference material, IAEA-C3, a secondary standard, that was analyzed in every wheel (analytical run) with the cocaine specimens. The mean value for IAEA-C3 was $\Delta^{14}C = 288.5 \pm 4.3‰$ ($n = 24$). Therefore, in subsequent interpretations we do not statistically distinguish among *individual recent single-value* $\Delta^{14}C$ *observations* that are less than 4.3‰ different from another. In absolute time, this translated to ~12 months between 2 coca specimens that were grown in 2009. However, for analyses of multiple specimens within a single seizure, the calculated average age differences could be less than 12 months depending on the standard deviation of the seizure population under consideration.

2.3. Conversion of ^{14}C observations into dates and time lag estimates

Calibration of the absolute date of production of modern coca leaf or cocaine specimens was conducted in a separate study [20], in which coca leaves were harvested at specific dates in Colombia over a 10-year period. In that study, cocaine was also extracted from coca leaves, allowing for determination of the $\Delta^{14}C$ *versus* year-of-production relationship of both modern coca leaf and cocaine specimens. The $\Delta^{14}C$-based calibration curve that allowed calculation of the date of growth determination was

$$T_c = \frac{\ln(\Delta^{14}C_c/d)}{f} \quad (2)$$

where T_c is the absolute date in years that a coca specimen was harvested in the field in Colombia, $\Delta^{14}C_c$ is the $\Delta^{14}C$ value of cocaine extracted from that coca leaf, $d = 2.422 \times 10^{45}$, and $f = -0.050072$ [20]. The exponential regression explained 97% of the observation variation.

To calculate the age of a seized cocaine specimen (A_{sc}) in months, we calculated the difference between T_c and the date in years that a specimen was seized (T_{sc}) as

$$A_{sc} = j \cdot (T_{sc} - T_c) \quad (3)$$

where j is the ratio the number of months (12) to days (365.25) in a year.

2.4. Statistical analyses

The cocaine $\Delta^{14}C$ data were analyzed graphically and statistically using Excel (Microsoft, Seattle, WA), KaleidaGraph (Reading, PA), and InStat (La Jolla, CA) software programs. Specimens with multiple $\Delta^{14}C$ measurements are reported as the mean value. Unless otherwise noted, the Mann–Whitney Test was used for all statistics where p-values are reported. Statistical analyses of cocaine specimens were conducted on the calculated "age in months" (A_{sc}). For all statistical analyses, statistical significance is defined as $\alpha < 0.05$.

Multi-specimen seizures are defined as cocaine seizures in which more than one specimen was acquired from the seizure. A total of 59 seizures fell into this category; the range was 2–18 (mean = 3.1) specimens per seizure. Multi-specimen seizures have the potential to bias interpretations within the dataset by over-representation when compared with single-specimen seizures. To avoid the potential for bias, a mean seizure age was calculated for each of the 59 major seizures. In that way, it was possible to compare seizures with multiple specimens with seizures having only a single specimen. Statistical results are presented using this mean value unless otherwise noted.

3. Results

On average for all specimens, there was a 22.8 ± 1.4 month lag (A_{sc}) between when cocaine was biosynthetically produced in coca leaves (as coca leaf growth based on [20]) and subsequently seized on a particular date (Fig. 2). The individual dates were calculated based on the difference between the expected $\Delta^{14}C$ value of a cocaine specimen on the date the specimen was seized *versus* the observed $\Delta^{14}C$. The regression line in Fig. 1 represents $\Delta^{14}C$ *versus* T, the relationship between $\Delta^{14}C$ measured on authentic specimens collected in the field *versus* dates of those collections [20]. Cocaine seizures plot above the line, with varying A_{sc} values that could be associated with cocaine extraction process, packaging, transportation, and storage factors. The

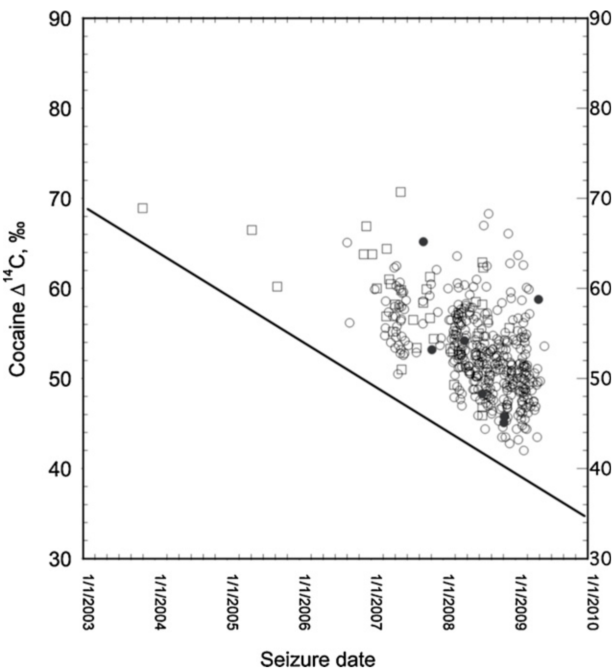

Fig. 1. A plot of the $\Delta^{14}C$ in cocaine specimens *versus* seizure date for specimens seized in different geographical regions: foreign seizures (open squares), domestic U.S. seizures (open circles), and U.S. Territory seizures (filled circles) of cocaine. Shown also is a linear regression of the authentic coca leaf acquisition dates against the calculated $\Delta^{14}C$ value for cocaine base produced from each leaf based on [20].

cocaine $\Delta^{14}C$ dataset was evaluated for sampling biases or time trends in A_{sc} values of specimens provided for analysis. None were detected as there were no significant differences in A_{sc} values of cocaine specimens seized in 2007–2009 time period (Fig. 1).

There were no *a priori* age distribution expectations for A_{sc} values of the seized cocaine specimens. Fig. 2 shows that the ages of the seized cocaine specimens were consistent with a normal distribution, with highest values in the 15–25-month age interval. There were no indications of multi-peaked distributions within the data set.

Cocaine HCl and cocaine base seizures did not differ in A_{sc} values, irrespective of how the comparisons were constructed.

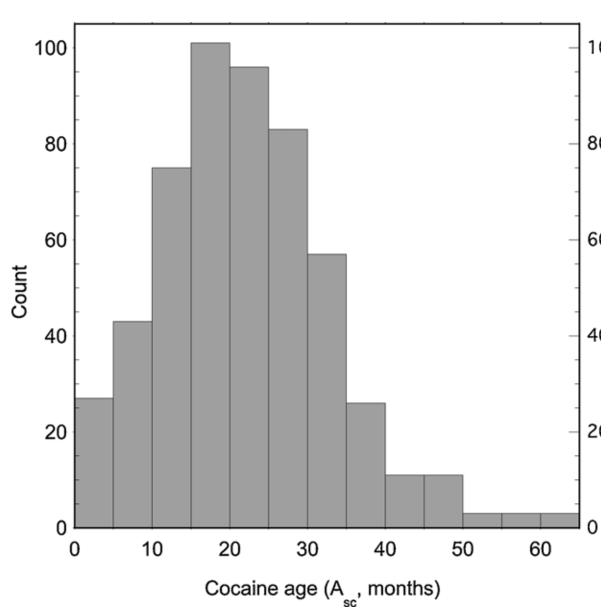

Fig. 2. A frequency histogram of the calculated ages (A_{sc}) of seized cocaine specimens.

Data were first analyzed by assigning all of the seized cocaine specimens into one of two categories: cocaine HCl and cocaine base. We then compared the ages of cocaine specimens classified into one of these two groups. There were no statistically significant differences in mean ages of cocaine HCl (mean = 22.4 months) *versus* cocaine base (mean = 24.1 months) ($p = 0.2484$, $U' = 19{,}102$). The significance of these observations is not clear with the limited data available, but it is perhaps surprising that seized cocaine base and HCl specimens did not differ in age.

Cocaine specimens were then analyzed with respect to by region-of-seizure. When foreign-seized cocaine base and cocaine HCl were compared, there was no statistically significant difference in mean ages of cocaine HCl (mean = 21.2 months) *versus* cocaine base (mean = 25.6 months) ($p = 0.5303$, $U' = 129.50$). We then considered comparisons based on domestic U.S. *versus* foreign seizure locations. We examined the dataset to determine whether there were age-based differences between foreign and domestically seized cocaine (lumping base and HCl specimens since these two populations were not different). When the two populations were compared, there was no statistically significant difference in mean ages of domestic (mean = 22.6 months) and foreign-seizure populations (mean = 24.7 months) of combined cocaine HCl and cocaine base populations ($p = 0.2625$, $U' = 9710.5$). When foreign specimens, seized only in South and Central America (mean = 25.7 months), were compared with all other foreign seizures (mean = 23.9 months) they were not statistically different in age ($p = 0.6253$, $U' = 307.50$). Again, the significance of these observations is not clear with the limited data available, but it is perhaps surprising.

When A_{sc} values of the domestic population of cocaine HCl (mean = 22.0 months) and foreign population of cocaine HCl (mean = 25.1 months) were compared, there was no statistically significant difference in mean ages ($p = 0.1374$, $U' = 6332.5$). When the domestic population of cocaine base (mean = 24.0 months) and foreign population of cocaine base (mean = 21.2 months) were compared, there was no statistically significant difference in mean ages ($p = 0.7421$, $U' = 299.50$).

There was no statistically significant difference in mean ages of domestic U.S. seizures (mean = 22.6 months) and U.S. Territory (mean = 24.4 months) cocaine seizure populations for base and HCl combined ($p = 0.8465$, $U' = 1343.5$).

When the domestic (mean = 22.0 months) and U.S. Territory (mean = 20.3 months) populations of cocaine HCl were compared, there was no statistically significant difference in mean ages ($p = 0.4172$, $U' = 924.50$). There were too few values to make comparisons between domestic cocaine base and U.S. Territory-seized cocaine base.

Collectively, these results indicated that A_{sc} values for cocaine base and cocaine HCl specimens, could be lumped in further age-related analyses since none of the populations were statistically different.

There were no U.S. region-specific differences in the ages of seized cocaine specimens. To determine whether there were age-based differences in cocaine by domestic region, each domestic cocaine base and hydrochloride specimen was assigned to one of seven specific regions: Central (median age = 19.9 months), East (median age = 22.0 months), Midwest (median age = 26.9 - months), South (median age = 21.0 months), Southwest (median age = 22.1 months), West (median age = 22.7 months), and U.S. Territory (median age = 19.5 months). A Kruskal–Wallis non-parametric analysis of variance (ANOVA) detected no significant differences in the calculated age-in-month median values between regions ($p = 0.7005$, Kruskal–Wallis statistic = 3.824), likely because of limited sample sizes in the statistical analyses.

Cocaine specimens were classified as "CSP," part of the Cocaine Signature Program at the DEA-STRL, or as "street" seizures, not related to the CSP. Whereas CSP specimens were of a large size >10 kg, street-seizure specimens were <28 g. CSP seizures consisted of foreign and domestic cocaine HCl specimens, whereas street seizures represent U.S. domestic-only seizures and included both cocaine base and HCl specimens. U.S. (including U.S. Territories) street seizures (mean = 24.6 months) of cocaine were 3.6 months older than all CSP seizures (mean = 21.0 months) and this difference was statistically significant ($p = 0.0043$, $U' = 20101$). Thus, street-level cocaine seizures were statistically older than the larger CSP seizures.

When only domestic (not including U.S. Territories) street and CSP specimens were considered in a comparison, there was still a significant difference in average ages of street seizure specimens (mean = 24.6 months) and CSP specimens (mean = 21.3 months) ($p = 0.0118$, $U' = 18947$). On average, street seizures were 3.2 months older than CSP seizures.

Seizures of large cocaine shipments are younger than seizures of small cocaine shipments. The CSP components of the dataset were used to evaluate the effect of seizure size on seizure date. Seizures varied in size from small street seizures without masses recorded, to larger CSP and foreign seizures weighing between a few grams and in one instance, over 15,000 kg. There were 59 instances where multiple specimens had been collected and analyzed from a single seizure (domestic, $n = 56$; foreign, $n = 3$). The average number of independent specimens analyzed per seizure was 3.1, with a range between 2 and 18.

The ages of different cocaine seizure sizes were calculated and specimens were assigned to one of four categories: <150 kg and <24 months, <150 kg and >24 months, >151 kg and < 24 months or >151 kg and >24 months. Fisher's Exact test showed statistically significant differences in cocaine ages based on seizure size. Fishers Exact test was used on all cocaine seizures for which seizure size data were available (CSP and Foreign combined, excluding street seizures) (one-sided $p = 0.0242$) and repeated for CSP seizures only (one-sided $p = 0.0479$). These statistical results indicated that large cocaine seizures are younger than smaller seizures. However, Fishers Exact test does not indicate the average ages of specimens in the different categories. For CSP and foreign seizures of <150 kg, the average age was 22.3 months ($n = 238$). For CSP and foreign seizures of >150 kg, the average age was 18.2 months ($n = 30$). These two values are statistically different from each other ($p = 0.0174$, $U' = 4415.5$).

Based on these and earlier results, the average time lag between coca leaf production and appearance at the street level can be partitioned into several approximate time periods:

- 3 months = approximate age of leaf at harvest (assumes typical 3 months between harvests).
- 18.2 ± 1.4 months = average age of large bulk CSP and foreign seizures.
- 22.3 ± 0.6 months = average age of a small bulk CSP and foreign seizures.
- 24.6 ± 1.1 months = average age of a U.S. street seizure.

The pattern above strongly suggested that the largest component of the time lag between coca leaf production and appearance of a street cocaine specimen was associated with time before cocaine interception at the CSP level. That lag of well over a year may have been associated with cocaine HCl production (very unlikely) or time associated with cocaine accumulation and/or transit to the United States.

Very small sample sizes allowed for limited data interpretation of cocaine seized in different countries. Seizures in Bolivia (age = 29.5 months, $n = 11$), Brazil (age = 18.5, $n = 1$), Colombia (age = 16.2 months, $n = 2$), Ecuador (age = 21.0 months, $n = 3$), and Peru (age = 31.5 months, $n = 3$) may or may not have been different from each other, but are not interpretable based on the limited sample sizes.

Table 2
$\Delta^{14}C$ and age in months for 18 different specimens analyzed in a single 638-kg cocaine seizure from the Eastern Pacific.

Utah ID	Source identifier	$\Delta^{14}C$ (‰) cocaine	Age (months)
440	C7568A	46.9	11.4
451	C7568B	44.8	5.9
438	C7568C	47.3	12.5
446	C7568D	46.3	9.9
447	C7568E	47.0	11.7
443	C7568F	45.4	7.5
442	C7568G	43.8	3.6
441	C7568H	44.0	3.9
493	C7568I	49.3	17.6
485	C7568J	54.5	31.1
494	C7568K	43.2	1.9
492	C7568L	48.3	15.1
486	C7568M	46.0	9.1
488	C7568N	47.0	11.6
484	C7568O	46.0	9.2
487	C7568P	47.9	14.0
498	C7568Q	49.0	16.9
496	C7568R	45.6	8.0
		Mean	11.2
		Standard deviation	6.7
		Count	18
		Minimum	1.9
		Maximum	31.1

Large cocaine seizures represented accumulations of different-age specimens. A total of 59 seizures were each sub-sampled between 2 and 18 times. A single 638-kg seizure from the Eastern Pacific represented 18 distinct specimens. The mean age of this cocaine seizure was 11 months, however the range of individual specimens was 2–31 months, varying more than 11‰ in ^{14}C. Table 2 summarizes the $\Delta^{14}C$ (‰) and age in month statistics for this unique seizure. Two additional seizures, one from Florida and one from Illinois, were sub-sampled and analyzed 6 and 9 times, respectively. The seizure from Florida ranged 5.8‰ in $\Delta^{14}C$; the seizure from Illinois ranged 8.8‰ in $\Delta^{14}C$. By age in months, the Florida specimens ranged 14.8 months, the specimens from Illinois, almost 22.7 months.

At this time, no clear conclusion can be made about whether or not the observed range in cocaine ages in a large seizure is typical of all cocaine seizures because of the limited number of different analyses within a single seizure. However, the available data suggest that large seizures often represented a compilation of cocaine accumulated over time before transiting to the United States.

4. Discussion

Our previous work [20] confirmed that $\Delta^{14}C$ were a useful tool to date the age of production of cocaine. The ^{14}C content in the atmosphere peaked in 1963 and since that time the ^{14}C content of the atmosphere has decreased as photosynthesis by land plants and marine algae take up $^{14}CO_2$ and store it within organic compounds. The exponential decrease in ^{14}C content of coca leaves and extracted cocaine specimens over time makes ^{14}C contents a more sensitive analytical tool for specimens acquired in the 1980s and 1990s than today. Nevertheless, with an analytical precision of about 4‰ for a recent individual observation, the signal-to-noise ratio still provides information useful to U.S. policy makers for estimating transit times for the time interval between coca leaf production and its arrival and street-level distribution in the United States.

This study has provided the first quantitative data on the time lag between coca production and street seizure of cocaine. The time lag between coca growth in South America and cocaine seizure in the United States averaged 24.6 months in the 2008–2009 time period. This time lag incorporates all steps on the way between plant growth and cocaine arrival in a city in the U.S., including time associated with growth in the field between harvest (3 months), extraction of cocaine from coca leaf, and the various transit stages between Colombia and the U.S. Based on the cocaine specimens analyzed, there is no evidence to suggest that transit times for cocaine base were different from cocaine HCl. It is not clear whether or not the similarity in-transit times for cocaine base *versus* cocaine HCL is reasonable and we are unaware of independent data relevant to this point. There were no statistical differences in the average time lag for cocaine arrival into different parts of the U.S. or its territories. If the results of this study are verified, then $\Delta^{14}C$ measurements could be a useful metric for the next several years to evaluate effectiveness of different drug eradication and interdiction policies.

Domestic and international bulk cocaine specimens seized and sampled as part of the CSP were on average 3.6 months younger than U.S. street seizures. When only domestic CSP specimens are considered in the comparison, CSP seizures were still 3.2 months younger than street seizures. Given that CSP seizures tended to be larger, in transit seizures before cocaine had arrived at the street level, these time-lag differences were expected. The average time lag of ~3–4 months between CSP- and street-seizures for cocaine suggests that traffic transit time into the U.S. is relatively rapid without extensive time delays. Taken together, the ^{14}C data suggest that the time between coca leaf growth and CSP seizure is far greater than the time lag between large CSP seizure and street-level seizures. While this observation may not come as a surprise, the independent confirmation lends credence to an expected delay as cocaine is parceled out in the illicit distribution chain.

Larger in-transit cocaine seizures were statistically younger than street-seized cocaine and larger cocaine seizures were on average younger than smaller cocaine seizures. Again, these observations may not come as a surprise, but independent $\Delta^{14}C$ data provided confirmation. The mean $\Delta^{14}C$ value for each of these seizures showed a statistically significant relationship between seizure sizes and age of a seized cocaine specimen, suggesting that large CSP cocaine seizures were statistically *younger* than smaller CSP seizures. This pattern was confirmed both with and without foreign CSP seizures included in the analyses. Following the logic that cocaine is transited as larger shipments before being subdivided for further distribution, these patterns make sense. On the other hand, based on the limited information available for this study, it is equally plausible that both large and small CSP seizures left the country of origin at the same time, but that larger shipments made it to the U.S. faster. Because of the limited information available, it is not possible to delineate between these two possibilities. However, the $\Delta^{14}C$ data do suggest that there is some accumulation of cocaine prior to its shipment out of South America or storage during transit to the United States.

For large seizures, it appears that cocaine may have been accumulated prior to arrival in the United States. Three of the seizures analyzed contained 6–18 independent specimens, allowing for evaluation of the age distributions among specimens. Within each of these three seizures, the average $\Delta^{14}C$ value ranged from 5.8‰ to 11.1‰, which exceeded a 1-year change in coca ^{14}C content. These data suggest that in these large shipments cocaine may have been accumulated for a year or more before attempted entry into the United States. Analyses of more of these larger seizures in the future may provide more insights into the production-to-distribution strategies of cocaine traffickers, especially in response to DEA-led interdiction efforts.

The $\Delta^{14}C$ data allow a quantitative evaluation of the effectiveness of cocaine-reduction policies using age-based cocaine seizure data. For instance, is it possible to assess the implications of eradication and/or increased seizure efforts in Colombia on reducing the flow of cocaine into the United States? Without a basic understanding of the time lags between coca leaf production and cocaine seizure, it will be difficult to quantitatively assess the impacts of supply-reduction efforts on illicit drug deliveries into the United States. Data on the ages of cocaine specimens analyzed in this study on cocaine should aid U.S. policy makers as they allocate resources at different levels to reduce cocaine availability in the U.S. Using radiocarbon observations, the results showed that on average, traffickers required approximately 24 months between growth of the coca leaf in Colombia and its arrival at the street level in the United States. Using this time lag estimate, one has a quantitative parameter to monitor the effectiveness of a drug policy. That is, given a policy change, is there a detectable change in the time lag between cocaine production and street-level distribution in the United States.

Finally, the results of this study indicate that larger CSP cocaine seizures might represent cocaine accumulated over multiple harvests rather than simply a single-season production. Further analyses will be required to effectively conclude the extent to which large shipments (on the order of tons) represented accumulated *versus* current-season's production. The ramification of having and applying this information has significant policy and law enforcement implications for both the source and consumer ends of the cocaine-supply routes.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.forsciint.2011.05.003.

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