A MODEL FOR CALCULATING FRESHWATER RESERVOIR OFFSETS ON AMS-DATED CHARRED, ENCRUSTED COOKING RESIDUES FORMED FROM VARYING RESOURCES

John P Hart
Research and Collections Division, New York State Museum, 3140 Cultural Education Center, Albany, NY 12230, USA.
Email: jph_nysm@mail.nysed.gov.

ABSTRACT. The freshwater reservoir effect (FRE) hypothesis suggests that ancient carbon from aquatic organisms incorporated into AMS-dated charred, encrusted cooking residues on interior pottery walls produces old apparent radiocarbon ages. This hypothesis has been used primarily in northern European final Mesolithic contexts to explain 14C ages on cooking residues that are thought to be too old relative to 14C ages obtained on terrestrial samples, resulting in so-called freshwater reservoir offsets (FROs). More recently, the hypothesis has been cited in interpretations of 14C ages from residues in the North American Plains and elsewhere. This article presents a model using an Excel spreadsheet that allows calculation of FROs with varying inputs of dead carbon and aquatic and terrestrial resources.

INTRODUCTION

As a result of the development of accelerator mass spectrometry (AMS) radiocarbon dating, precise, accurate 14C ages can be obtained on very small amounts of charred organic material. Since its introduction in the early 1980s, archaeologists have taken advantage of this technique to obtain 14C ages on a wide array of objects of direct chronological interest (e.g. individual cereal grains). Since the late 1980s, this has included charred cooking residues formed during water-based cooking and encrusted on the interior walls of pottery and other durable cooking vessels (e.g. Lovis 1990). Pottery can be a critical source of information about prehistoric lifeways, and it is subject to a wide array of analyses (e.g. Rice 1987; Skibo 2013). Obtaining direct dates on pottery through AMS assays on encrusted residues can allow firm chronological control of such analyses.

In the early 2000s, archaeologists working on final Mesolithic sites in northern Europe identified a potential problem with AMS dates on charred cooking residues (Fischer and Heinemeier 2003). Specifically, they argued that ancient carbon from freshwater reservoirs resulted in old apparent ages on charred cooking residues when aquatic organisms were cooked in the pots. This freshwater reservoir effect (FRE) hypothesis has gained considerable traction among archaeologists investigating final Mesolithic sites in northern Europe as an explanation for what are interpreted to be too-old 14C ages from charred residues (e.g. Boudin et al. 2009; Philippsen et al. 2010; Crombé et al. 2013; Saul et al. 2013). Various articles have suggested the FRE has resulted in offsets between AMS assays on encrusted cooking residues and dates on short-lived terrestrial resources from the same archaeological contexts, so-called freshwater reservoir offsets (FROs; Keaveney and Reimer 2012). Recently, archaeologists working in the North American Plains have claimed that AMS dates on cooking residues exhibit FROs (Hohman-Craine and Sym 2012; Roper 2013).

There is no question that ancient carbon from carbonate (CO$_3^{-2}$) and bicarbonate (HCO$_3^{-}$) ions is present in freshwater bodies as a result of the weathering of carbon-rich rocks and unconsolidated materials as well as other sources. This has been known since the 1950s (e.g. Godwin 1951; Deevey et al. 1954; Broecker and Walton 1959) and is currently under investigation in several disciplines (e.g. Caraco et al. 2010; Zigah et al. 2012; Ishikawa et al. 2013; Philippsen and Heinemeier 2013).

What is questionable is the impact of the FRE on 14C ages obtained from residues. Interpretations in the foundational article on the FRE at three final Mesolithic sites in northern Europe (Fischer and Heinemeier 2003) were shown to be inaccurate—there was no statistically significant pattern for too-old ages on residues (Hart and Lovis 2007). Saul et al.’s (2013:4) recent publication of a series of 14C ages obtained on residues from one of the sites supports this result. AMS dates on charred...
residue from agricultural Neolithic sites in northern Europe have not been at issue (Crombé et al. 2013:557). The recent attributions of FROs in the central North American Plains (Roper 2013) have been questioned (Hart and Lovis 2014). Modeling, the paleolimnological record, and lipid analyses of residues suggest an absence of significant FROs for AMS-dated residues from sites in New York’s Finger Lakes region (Hart et al. 2013).

At issue are (1) the presence of ancient carbon reservoirs in pertinent bodies of water, and specific locations therein, at the appropriate periods of time, (2) the concentrations of ancient carbon in aquatic organisms from those bodies of water, and (3) the amount of carbon aquatic organisms contributed to the formation of a given residue. Via modeling it is possible to estimate the amount of raw fish with varying concentrations of dead carbon that would have had to contribute carbon to residue formation in order to produce a given FRO (Hart et al. 2013; Hart and Lovis 2014). The present article provides an Excel spreadsheet with the model (as an online Supplemental file), which allows manipulation of all important variables for 1–3 food resources.

RESIDUE FORMATION EXPERIMENTS AND OFFSETS

Important to constructing a model for FROs is an understanding of how charred encrusted cooking residues form. Residue-forming experiments and associated mathematical modeling have resulted in important insights into this process (Hart et al. 2007a, 2009; Lovis et al. 2011). Prior to these efforts, the assumption was that there was a linear relationship between the fractions of raw resources in a mixture cooked in water and residue carbon contribution by each resource. In the Western Hemisphere, it was expected that the fraction of maize (Zea mays ssp. mays), a C4-pathway plant, in a resource mixture with C3-pathway resources could be determined based on bulk δ13C values on residues (Hastorf and DeNiro 1985). Bulk δ13C values on residues formed from resource mixtures containing maize would be higher than bulk δ13C values on residues formed from cooking only C3-pathway resources. A linear relationship was hypothesized to occur between the fraction of raw maize in the resource mixture and δ13C values so that the presence and resource fraction of maize could be determined (e.g. Morton and Schwarcz 2004). However, the identification of maize phytoliths in residues from the Finger Lakes region of New York (Hart et al. 2003) with δ13C values in line with C3-pathway resource use suggested that the hypothesis was questionable (Hart et al. 2007a).

An initial set of residue-forming experiments using maize and one C3 plant (wild rice: Zizania aquatica or chenopodium: Chenopodium album) or white-tailed deer (Odocoileus virginianus) meat from a strictly C3 habitat, indicated that maize could contribute anywhere between 5% and 90% of the raw resource mixture before bulk δ13C values were high enough to suggest its presence (Hart et al. 2007a). In these experiments, the water was allowed to evaporate and the resource mixtures to thoroughly carbonize, thus representing the end-products of residue-forming episodes. The relationships between the fraction of maize in the resource mixture and the bulk δ13C values were nonlinear and varied considerably depending on the C3 resource. Mathematical modeling indicated that rather than the fraction that maize and the C3 resource contribute to the raw resource mixture it was the fraction of carbon in each resource that determined its contribution to residue formation. Each resource’s carbon content depended on its fat, carbohydrate, and protein content, which have different carbon fractions: approximately 0.80, 0.42, and 0.53, respectively (Hart et al. 2007a). The mathematical model produced good fits to the values obtained from the experimental residues.

A second round of experiments was conducted to determine if the amounts of carbon potentially contributed to residue formation by maize and C3 resources varied through time based on a series of timed-interval samples of material in suspension/solution (Hart et al. 2009). The results demonstrated that carbon mobilization from a particular resource over time determined its potential contribu-
tion to residue formation. However, these results did not obviate those of the first experiment—that it is a resource’s carbon fraction that ultimately determined its contribution to residue formation. This result is not limited to the resources used in the experiments; it is true of any resource.

$^{14}$C ages are based on the fraction of modern (1950) atmospheric $^{14}$C (FMC) contained in the assayed carbon. CO$_2$ produced from the residue for AMS dating derives from all of the resources that contributed carbon to the residue’s formation. If dead carbon is present in a body of freshwater and this carbon is metabolized by aquatic organisms, there is a potential that it will be incorporated into residues (Saul et al. 2013), whether or not an FRO occurs is determined by the fraction of residue carbon that is dead—the dead carbon fraction (DCF) of the residue. The DCF of a residue will decrease the FMC in the AMS-dated CO$_2$ and thus produce an old apparent $^{14}$C age. The amount of dead carbon contributed by an aquatic resource to residue formation determines the residue’s DCF and whether an FRO will occur.

Whether or not there is dead carbon in a freshwater body depends on the presence and extent of weathering of carbon-rich bedrock and/or unconsolidated material and other sources in the drainage basin. The concentrations of dead carbon in a freshwater body can vary significantly over time, between specific locations within the body, and by water column depth (Mullins et al. 2011; Keaveney and Reimer 2012; Zigah et al. 2012). DCF can vary between individuals of a given species as well as between species within a given body of water at any given time (Keaveney and Reimer 2012). As a result, the simple presence of fish or shellfish remains on an archaeological site does not necessarily implicate FROs in AMS-dated residues.

THE FRESHWATER RESERVOIR OFFSET MODEL

The FRO model presented here is based on the results of the residue-forming experiments and modeling (Hart et al. 2007a, 2009). Equations used in the FRO model were published in Hart et al. (2013). The model is made available here in an Excel spreadsheet to allow the direct calculation of FROs (Supplemental file). The spreadsheet allows manipulation of all model variables. Revisions to the equations published in Hart et al. (2013) include changes in variable notation to reflect decimal fractions rather than percentages, and a different formula for calculating the DCF of aquatic organisms. Each variable in the model is listed and explained below. A listing of variables and their abbreviations is presented in Table 1.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terrestrial resources</td>
<td>$R_1$, $R_2$</td>
</tr>
<tr>
<td>Aquatic resource</td>
<td>$R_3$</td>
</tr>
<tr>
<td>Resource carbon fraction</td>
<td>CF</td>
</tr>
<tr>
<td>Dead carbon fraction</td>
<td>DCF</td>
</tr>
<tr>
<td>Fraction modern carbon</td>
<td>F</td>
</tr>
<tr>
<td>Resource fraction</td>
<td>RFMC</td>
</tr>
<tr>
<td>Residue carbon fraction</td>
<td>RCF</td>
</tr>
<tr>
<td>Residue dead carbon fraction</td>
<td>RDCF</td>
</tr>
<tr>
<td>Residue fraction modern carbon</td>
<td>RFMC</td>
</tr>
<tr>
<td>Freshwater offset</td>
<td>FRO</td>
</tr>
</tbody>
</table>
Resource carbon fraction (CF): The model is based on one to three resources, which may include two terrestrial resources (R₁, R₂) and one aquatic resource (R₃). Typically, these will be resources that have been identified in the archaeological record for a given site component and are likely to have been cooked together in water. For each resource, the user assigns a CF value based on the resource’s fat, carbohydrate, and protein content. The following formula can be used to calculate the total carbon fraction for each resource (Hart et al. 2007a):

\[
CF_{Rn} = 0.8\text{Fat}_{Rn} + 0.42\text{Carbohydrate}_{Rn} + 0.53\text{Protein}_{Rn}
\]

Fat, carbohydrate, and protein values for a given resource can be obtained from the USDA National Nutrient Database for Standard Reference (http://ndb.nal.usda.gov/) or other published sources.

Dead carbon fraction (DCF): A DCF is assigned by the user for the aquatic resource (R₃). This is the fraction of dead carbon in the aquatic resource resulting from metabolizing ancient carbon. If assays are available on fish bone and on a terrestrial resource clearly associated with it in a secure archaeological context, DCF can be calculated using the following formula:

\[
\text{DCF} = \frac{\text{FMC}_T - \text{FMC}_A}{\text{FMC}_T}
\]

where \(\text{FMC}_T\) is the fraction modern (1950) carbon for the terrestrial resource and \(\text{FMC}_A\) is the fraction modern carbon for the aquatic resource. This assumes that the \(^{14}\text{C}\) age of the aquatic resource is older than that of the terrestrial resource. \(\text{FMC}_T\) and \(\text{FMC}_A\) may be obtained from the lab report on \(^{14}\text{C}\) ages. Alternatively, values can be selected by the user to observe how offsets change under varying DCFs.

Fraction modern carbon (FMC): The user supplies the fraction modern (1950) carbon of a terrestrial resource at a given age. This can be from the \(\text{FMC}_T\) used to calculate DCF, or one used to model FRO for a hypothetical \(^{14}\text{C}\) age.

Half-life: The user assigns a \(^{14}\text{C}\) half-life based on what the laboratory used for \(^{14}\text{C}\) dating. The default value is 5568 yr, which is used in all other formulae requiring a half-life value. Changing the half-life value here will automatically change the value in other formulae.

\(^{14}\text{C}\) age: The \(^{14}\text{C}\) age without a freshwater reservoir offset is calculated via the standard equation:

\[
^{14}\text{C}_{\text{age}} = \left( \frac{\ln(\text{FMC})}{-0.693} \right) \times ^{14}\text{C} \text{ half-life}
\]

Resource fractions (\(F_{R1}, F_{R2}, F_{R3}\)): These are the raw fractions of the three model resources. The spreadsheet has a series of values entered, but the values in any of the rows can be changed to meet the user’s needs.

Residue carbon fraction (RCF\(R_{R1}, R_{R2}, R_{R3}\)): The carbon fraction that each resource contributes to the modeled residue is calculated with the following equation (Hart et al. 2007a):

\[
\text{RCF}_{Rn} = \frac{F_{Ro} \times CF_{Rn}}{F_{R1} \times CF_{R1} + F_{R2} \times CF_{R2} + F_{R3} \times CF_{R3}}
\]

where \(Rn\) is \(R_1, R_2,\) or \(R_3\) depending on which modeled resource is considered (see spreadsheet).
A simplifying assumption is that each resource contributes carbon to the residue proportional to its carbon content alone. Residue-formation experiments and modeling suggest that the contribution of carbon by any given resource to residue formation will vary according to how rapidly its carbon is mobilized relative to other resources during water-based cooking and, as a result, the length of cooking time (Hart et al. 2009). The calculation of FROs in the model is based on RCFR not FR.

**Residue DCF (RDCF):** The DCF for the modeled residue is calculated by multiplying the RCF of the aquatic resource (R3) by the DCF of that resource as previously determined for the model (Hart et al. 2013):

\[
RDCF = RCF_{R3} \times DCF
\]

**Residue FMC (RFMC):** The modeled residue’s fraction modern (1950) carbon is determined with the following equation (Hart et al. 2013):

\[
RFMC = FMC - (FMC \times RDCF)
\]

**Residue ^14C age:** The modeled residue’s ^14C age is calculated with the standard formula:

\[
\text{Residue } ^{14}C_{\text{age}} = \left( \frac{\ln(RFMC)}{-0.693} \right) \times ^{14}C \text{ half-life}
\]

**Freshwater offset (FRO):** Freshwater offsets are calculated with the following formula (Keaveney and Reimer 2012):

\[
FRO = \text{Residue } ^{14}C_{\text{age}} - ^{14}C_{\text{age}}
\]

**MODEL TEST**

The model produces, of course, an almost perfect linear fit between DCP and FRO (Figure 1). In order to test the model, 12 mixtures of $CO_2$ from a source of dead carbon (smithing coke) and a carbonized late-prehistoric maize cob of known age were made and subjected to AMS dating. The maize cob and smithing coke were each ground into fine powders and then pretreated for AMS dating in the New York State Museum’s Geochemistry Laboratory following the Oxford Accelerator Radiocarbon Unit protocols as published in Brock et al. (2010). The pretreated powders were submitted to the Illinois State Geological Survey Geochronology Laboratory (lab code ISGS) to create varying mixtures of $CO_2$ from the two sources. The $CO_2$ mixtures were submitted to the W M Keck Carbon Cycle Accelerator Mass Spectrometry Laboratory at the University of California, Irvine (UCI) for AMS assay.

Because it is the presence of dead carbon in a residue that results in an FRO, the mixture of $CO_2$ from a late-prehistoric maize cob and a dead carbon source is an apt analogue for $CO_2$ obtained for AMS dating from residues containing dead carbon from fish. The source of the dead carbon is irrelevant; it is the fact that it has no $^{14}C$ that is relevant. The resulting $^{14}C$ ages were used to calculate DCF. Offsets were obtained by subtracting the $^{14}C$ age of the maize cob from the $^{14}C$ age of each $CO_2$ mixture. These offsets are compared to those predicted by the model (Table 2). Differences between expected and observed offsets are, in all but one case, less than 5 yr with an average of 3.08 yr. This indicates that the model performs well.
Table 2  Expected versus observed offsets for AMS dating experiment.

<table>
<thead>
<tr>
<th>ISGS#</th>
<th>FMC</th>
<th>¹⁴C age</th>
<th>DCF</th>
<th>Expected offset</th>
<th>Observed offset</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>A2697</td>
<td>0.9541</td>
<td>380</td>
<td>0.000000</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>A2702</td>
<td>0.9433</td>
<td>470</td>
<td>0.011320</td>
<td>91</td>
<td>91</td>
<td>0</td>
</tr>
<tr>
<td>A2703</td>
<td>0.9387</td>
<td>510</td>
<td>0.016141</td>
<td>132</td>
<td>130</td>
<td>2</td>
</tr>
<tr>
<td>A2698</td>
<td>0.9377</td>
<td>515</td>
<td>0.017189</td>
<td>141</td>
<td>139</td>
<td>2</td>
</tr>
<tr>
<td>A2706</td>
<td>0.9338</td>
<td>550</td>
<td>0.021277</td>
<td>175</td>
<td>172</td>
<td>3</td>
</tr>
<tr>
<td>A2705</td>
<td>0.9309</td>
<td>575</td>
<td>0.024316</td>
<td>200</td>
<td>197</td>
<td>3</td>
</tr>
<tr>
<td>A2701</td>
<td>0.9268</td>
<td>610</td>
<td>0.028613</td>
<td>236</td>
<td>233</td>
<td>3</td>
</tr>
<tr>
<td>A2710</td>
<td>0.9231</td>
<td>645</td>
<td>0.032491</td>
<td>268</td>
<td>265</td>
<td>3</td>
</tr>
<tr>
<td>A2707</td>
<td>0.9152</td>
<td>710</td>
<td>0.040771</td>
<td>338</td>
<td>334</td>
<td>4</td>
</tr>
<tr>
<td>A2704</td>
<td>0.9139</td>
<td>725</td>
<td>0.042134</td>
<td>349</td>
<td>345</td>
<td>4</td>
</tr>
<tr>
<td>A2708</td>
<td>0.9120</td>
<td>740</td>
<td>0.044125</td>
<td>366</td>
<td>362</td>
<td>4</td>
</tr>
<tr>
<td>A2709</td>
<td>0.8963</td>
<td>880</td>
<td>0.060581</td>
<td>503</td>
<td>502</td>
<td>1</td>
</tr>
<tr>
<td>A2711</td>
<td>0.8698</td>
<td>1120</td>
<td>0.088356</td>
<td>735</td>
<td>743</td>
<td>–8</td>
</tr>
</tbody>
</table>

APPLYING THE MODEL

Perhaps the greatest potential use of the model is to determine the RCF₉ from a given resource mixture needed to produce particular FROs at a given DCF₉. For example, using Ward and Wilson’s (1978) technique as implemented in CALIB 6.01 (Stuiver and Reimer 1993), a significant offset for a ¹⁴C age of 5100 ± 20 BP is 56 ¹⁴C yr. The RCF₉ (lean fish) needed to produce a 56 ¹⁴C yr offset ranges between 0.0343 and 0.6860 given a DCF₉ range of 0.2 to 0.01 (Table 3). The model can also be used to estimate the fraction of raw fish (F₉) needed in a resource mixture to produce a given FRO given the CF of each modeled resource and the simplifying assumption mentioned above. In the present example, F₉ ranges from 0.117 to 0.8995 for a DCF range of 0.20 to 0.01.
Table 3  \( F_{R3} \) and \( RCF_{R3} \) needed to produce a 56 \( {^{14}}C \) yr offset for a \( {^{14}}C \) age of 5100 ± 20 BP.

<table>
<thead>
<tr>
<th>DCF ( R_{3} )</th>
<th>( F_{R3} )</th>
<th>( RCF_{R3} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.20</td>
<td>0.117</td>
<td>0.0343</td>
</tr>
<tr>
<td>0.15</td>
<td>0.155</td>
<td>0.0469</td>
</tr>
<tr>
<td>0.10</td>
<td>0.216</td>
<td>0.0688</td>
</tr>
<tr>
<td>0.05</td>
<td>0.375</td>
<td>0.1387</td>
</tr>
<tr>
<td>0.04</td>
<td>0.440</td>
<td>0.1742</td>
</tr>
<tr>
<td>0.03</td>
<td>0.530</td>
<td>0.2324</td>
</tr>
<tr>
<td>0.02</td>
<td>0.661</td>
<td>0.3436</td>
</tr>
<tr>
<td>0.01</td>
<td>0.8995</td>
<td>0.6860</td>
</tr>
</tbody>
</table>

Another use of the model is to determine how likely the difference between two \( {^{14}}C \) ages is an FRO. For example, Fischer and Heinemeier (2003) suggest that an offset of 290 ± 64 \( {^{14}}C \) yr (2\( \sigma \) range 162–418 \( {^{14}}C \) yr) between \( {^{14}}C \) ages on charred rootlet contained in pottery fabric and encrusted residue on the same sherd is an FRO. Listed in Table 4 are the \( F_{R3} \) and \( RCF_{R3} \) values needed to obtain this offset range from the \( {^{14}}C \) age on the rootlet (5095 ± 45 BP) at varying DCFs assuming a lean fish such as pike. With a DCF of 0.2, \( RCF_{R3} \) needs to be 0.0997 to 0.2871, and \( F_{R3} \) 0.292 to 0.558. With the lowest DCF to produce the full 2\( \sigma \) range, 0.10, an \( RCF_{R3} \) of 0.1992 to 0.5064 and \( F_{R3} \) of 0.481 to 0.7926, respectively, are needed to produce the full 2\( \sigma \) offset range. For a DCF of 0.04, a 162-yr FRO requires an \( RCF_{R3} \) of 0.4979 and \( F_{R3} \) 0.787, while a 290-yr FRO requires an \( RCF_{R3} \) of 0.8841 and \( F_{R3} \) of 0.966; a 418-yr FRO is not possible. With a DFCR3 of 0.02, a 162-yr FRO requires an \( RCF_{R3} \) of 0.9963 and \( F_{R3} \) 0.999—essentially all of the residue’s carbon must have originated from fish; thus, 290 and 418 yr FROs are not possible.

A DCF for contemporaneous fish at the Åkonge site in Denmark can be estimated based on data in Fischer and Heinemeier (2003:456), who calculate a mean \( {^{14}}C \) age of 5347 ± 19 BP for fish bone in layer 3b. This is a 232-yr FRO from the 5095 \( {^{14}}C \) age on the rootlet. Using the equation above, the average DCF for fish is 0.0309. At this DCF, an FRO of 290 yr is not possible. An FRO of 162 yr, using the CF value for pike of 0.1067, requires a \( RCF_{R3} \) of 0.646. The oldest \( {^{14}}C \) age on fish bone from layer 3b at Åkonge is 5565 ± 40 on tench, producing an offset from the rootlet \( {^{14}}C \) age of 470 \( {^{14}}C \) yr and a DCF of 0.0568. With this DCF, and using the CF value of 0.393 for carp, a fish related to tench, an \( RCF_{R3} \) of 0.351 is needed to produce an FRO of 162 yr, 0.625 for an FRO of 290 yr, and 0.893 for an FRO of 418 yr.

Table 4  \( F_{R3} \) and \( RCF_{R3} \) needed to produce a 290 ± 64 \( {^{14}}C \) yr 2\( \sigma \) FRO range for a \( {^{14}}C \) age of 5095 ± 45 BP.

<table>
<thead>
<tr>
<th>DCF ( R_{3} )</th>
<th>( 162 {^{14}}C ) yr FRO</th>
<th>( 290 {^{14}}C ) yr FRO</th>
<th>( 418 {^{14}}C ) yr FRO</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F_{R3} )</td>
<td>( RCF_{R3} )</td>
<td>( F_{R3} )</td>
<td>( RCF_{R3} )</td>
</tr>
<tr>
<td>0.20</td>
<td>0.2920</td>
<td>0.0997</td>
<td>0.4450</td>
</tr>
<tr>
<td>0.15</td>
<td>0.3604</td>
<td>0.1332</td>
<td>0.5405</td>
</tr>
<tr>
<td>0.10</td>
<td>0.4810</td>
<td>0.1992</td>
<td>0.6710</td>
</tr>
<tr>
<td>0.05</td>
<td>0.7110</td>
<td>0.3977</td>
<td>0.9000</td>
</tr>
<tr>
<td>0.04</td>
<td>0.7870</td>
<td>0.4979</td>
<td>0.9660</td>
</tr>
<tr>
<td>0.03</td>
<td>0.8799</td>
<td>0.6629</td>
<td>—</td>
</tr>
<tr>
<td>0.02</td>
<td>0.9990</td>
<td>0.9963</td>
<td>—</td>
</tr>
</tbody>
</table>
The earlier analysis of $^{14}$C ages from layer 3b at Åkonge indicated no statistically significant difference in the suite of $^{14}$C ages with the exception of one outlier (Hart and Lovis 2007). Such an outlier is not unexpected in a large suite of $^{14}$C ages from an archaeological component. Whether this outlier is the result of laboratory error, FRE, or some other factor cannot be determined. It is not possible to carry out similar analyses of other final Mesolithic sites where FROs are suggested because of questionable associations between AMS-dated terrestrial resources, AMS-dated fish bone, and pottery with AMS-dated residues (Phillipsen and Heinemeier 2013); AMS-dated fish bone from purportedly the same context as AMS-dated residues having younger $^{14}$C ages than the residues (Boudin et al. 2009); a wide spread of $^{14}$C ages on terrestrial resources and fish bone (Phillipsen and Heinemeier 2013); uncertain chronological contexts of pottery with AMS-dated residues and AMS-dated terrestrial resources and fish bone (Phillipsen et al. 2010); and a lack of $^{14}$C assays on fish bone (Crombé et al. 2013; Roper 2013).

We know from northeastern North America on the basis of phytolith, starch, lipid, and isotope analyses that it is uncommon for a single resource to have contributed all carbon to residue formation (Boyd and Surette 2010; Hart et al. 2007b; Messner et al. 2008; Reber and Hart 2008; Ravielle 2010). Similar levels of analyses have not been completed in many of the locations where FROs are assumed.

CONCLUSIONS

Archaeologists working on the final Mesolithic of northern Europe have cited the FRE hypothesis as an explanation for what they consider to be too-old $^{14}$C ages obtained from AMS dating charred cooking residues adhering to the interior walls of pottery sherds. Archaeologists working in other parts of the world have also begun to cite the FRE hypothesis as an explanation for what they perceive to be too-old $^{14}$C ages obtained on residues. The model presented here provides archaeologists with a tool to estimate the amount of raw fish needed to have contributed carbon to residue formation to produce a given FRO at a specific DCF. It provides a means of determining the fraction of carbon from fish in residue formation at a given DCF to produce a specific FRO. The DCF for a particular archaeological context can be estimated by obtaining $^{14}$C ages on fish bone and terrestrial resources from what are interpreted to be secure archaeological contexts. The model can also be used to determine the likelihood that any source of old or ancient carbon could have produced a given offset, such as wood ash or shell tempering, respectively (Hart and Lovis 2014). Systematic application of the model provides a basis on which to evaluate the potential for FRO to be responsible for older than expected $^{14}$C ages on charred cooking residues.

ACKNOWLEDGMENTS

I thank Robert Feranec and Hong Wang for their contributions to the AMS-dating experiment and Feranec, Wang, and William Lovis for useful comments and suggestions on earlier versions of this paper.

REFERENCES


Crombé P, Robinson E, Van Strydonck M, Boudin M.


