Reporting C-14 activities and concentrations

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REPORTING ^{14}C ACTIVITIES AND CONCENTRATIONS

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ABSTRACT. Three modes of reporting ^{14}C activities are in use, in part analogous to the internationally accepted (IAEA) conventions for stable isotopes: (1) *absolute activity*, the specific activity of ^{14}C or the activity per gram of carbon; (2) *activity ratio*, the ratio between the absolute activities of a sample and the standard; and (3) *relative activity*, the difference between the absolute activities of a sample and standard material, relative to the absolute standard activity. The basic definitions originate from decisions made by the radiocarbon community at its past conferences. Stuiver and Polach (1977) reviewed and sought to specify the definitions and conventions. Several colleagues, however, have experienced inadequacies and pitfalls in the definitions and use of symbols. Furthermore, the latter have to be slightly amended because of the use of modern measuring techniques.

This paper is intended to provide a consistent set of reporting symbols and definitions, illustrated by some practical examples.

1. INTRODUCTION

This paper is meant to update the conventions and symbols recommended for the reporting of radiocarbon data in Stuiver and Polach (1977), henceforth abbreviated as S&P77.

The basic definitions are straightforward and will be repeated here. However, the use of symbols will be made more transparent by limiting their number and clarifying their meaning with the addition of a limited number of super- and subscripts.

The *absolute (specific) ^{14}C activity*, that is, the ^{14}C radioactivity (in Bq or, conventionally, in disintegrations per minute [dpm] per gram of carbon) is given the symbol

$$^{14}A \quad (\text{in dpm/gC}) \ . \tag{1}$$

The vast majority of ^{14}C laboratories are unable to make such absolute measurements: the measuring efficiency is unknown. Also, in general, the absolute ^{14}C content of a sample is not relevant. Therefore, the sample activities are compared with the activity of a reference material, the international standard. In practice, the number of ^{14}C registrations (= β counts from ^{14}C decay in radiometric detectors such as proportional counters and liquid scintillation counters; registrations of ^{14}C concentration in AMS systems) is related to the number of registrations from the reference sample under equal conditions. This results in the introduction of a *^{14}C activity ratio* or *^{14}C concentration ratio*:

$$^{14}a = \frac{\text{measuring efficiency} \times {}^{14}A_{sample}}{\text{measuring efficiency} \times {}^{14}A_{reference}} = \frac{{}^{14}A_{sample}}{{}^{14}A_{reference}}$$
$$= \frac{{}^{14}C \text{ decay rate in the sample}}{{}^{14}C \text{ decay rate in the ref. material}} = \frac{{}^{14}C \text{ concentration in the sample}}{{}^{14}C \text{ concentration in the ref. material}} \ . \tag{2}$$

Because in the numerator and denominator of the last two fractions, the detection efficiencies are equal for sample and standard, **the use of the ratio ^{14}a is adequate for any type of measuring technique.** Henceforth, **we will use the symbol ^{14}A for the *^{14}C content* (radioactivity as well as concentration) of a sample,** whether the analytical technique applied is radiometric or mass spectrometric (AMS).

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We have chosen to have symbols refer to ^{14}C by prefixing the superscript "14", as in ^{14}A, ^{14}a, and $^{14}\delta$ (likewise $^{13}\delta$), because it leaves space for other superscripts and it makes the symbols less complicated; compare, for instance, $^{14}\delta^0$ with $\delta^{14}C^0$. Moreover, these symbols are unambiguous.

Under natural circumstances the values of ^{14}a are between 0 and 1. In order to avoid a large number of decimals, it is general practice to report these values in percent (%). However, it should be noted that this practice does not change the fact that ^{14}a is a number generally between 0 and 1. The consequence is that the factor 10^2 should *not* enter into equations (as $^{14}a/10^2$).

In some cases the differences in ^{14}C content between samples are small. Therefore, the use of relative abundances has been adopted from the stable-isotope field, in this case the *relative ^{14}C content (activity or concentration)*, $^{14}\delta$, defined as the difference between sample and standard ^{14}C content as a fraction of the standard value:

$$^{14}\delta = \frac{^{14}A - {}^{14}A_{Ref}}{^{14}A_{Ref}} = \frac{^{14}A}{^{14}A_{Ref}} - 1 = {}^{14}a - 1 \quad .$$

(3)

The values of δ are small numbers and therefore generally given in per mill (‰). However, we want to stress that ‰ is equivalent to the factor 10^{-3}; δ is thus dimensionless and not a unit. As with ^{14}a defined above, there is no need (it is actually incorrect) to add 10^{-3} to δ in mathematical equations.

A ^{14}C *reference material* or *standard* was chosen to represent as closely as possible the ^{14}C content of carbon in naturally growing plants. The ^{14}C content of the standard material itself does not need to be, in fact is not, equal to the *standard ^{14}C content*. The definition of the standard ^{14}C activity is based on 95% of the specific activity of the original NBS oxalic acid (Ox1) in the year AD 1950 (Karlén et al. 1966), as will be discussed in more detail later.

Before the definition of standards can be completed, two factors have to be discussed that complicate the standardization of ^{14}C results and the respective symbols.

1.1. The Question of Isotope Fractionation

During the transition of carbon from one compound to another—for example, the assimilation of CO_2 by plants or the exchange of CO_2 between the air and surface water—isotope fractionation occurs for ^{13}C as well as ^{14}C. The laboratory treatment of sample materials may also introduce an isotopic change, for instance by an incomplete chemical reaction. If this fractionation were neglected, samples of different chemical composition (carbonate, plants) but made of carbon of the same age (determined by atmospheric CO_2) would seem to have different ages.

Therefore, in order to make ^{14}C ages comparable, a correction has to be applied for this fractionation effect. The theoretical relation between ^{14}C and ^{13}C fractionations is written as

$$\frac{^{14}A_N}{^{14}A} = \left(\frac{^{13}R_N}{^{13}R} \right)^\theta \quad ,$$

(4)

where ^{14}A and ^{13}R refer to the measured activity, $^{14}A_N$ to the fractionation-corrected or *normalized* ^{14}C activity, and $^{13}R_N$ (or rather $^{13}\delta_N$) is an internationally adopted standard value. This value is $^{13}\delta_N$

= −25‰ with respect to VPDB (the PDB standard is discontinued and replaced by Vienna PDB with NBS19 as the calibration standard for $^{13}\delta$ and $^{18}\delta$; Gonfiantini 1984), being a representative average of the majority of organic samples in nature. Also the standard activity has to be normalized in the same way. The only exception is that, for historical reasons, the old Oxalic Acid standard (Ox1) is normalized to its own $^{13}\delta$ value of −19‰.

For natural processes the value of θ is approximately 2 (Craig 1954). Since we have no reliable experimental evidence for the true value of θ (in cases where the relation between the fractionations could be measured [Meijer and Li 1998] or calculated [Mook 2000], the θ value is rather about 1.9), and because this uncertainty is irrelevant in light of the analytical precision of ^{14}C measurements, we will use $\theta = 2$ as a sufficient approximation.

1.2. The Question of Radioactive Decay

For radioactive samples a measured activity depends on the time of measurement, t_m:

$$^{14}A(t_m) = {}^{14}A(t_0)e^{-\lambda\Delta t} \qquad \text{or} \qquad {}^{14}A = {}^{14}A^0 e^{\lambda(t_m - t_0)} \quad , \tag{5}$$

which is also valid for the standard material. Therefore, when reporting an absolute ^{14}C content, the year for which the value is valid must be specified. The same is true for the standard. The year of reference was chosen to be AD 1950; the superscript ^{0} refers to this "year 0". The standard activity thus is valid for the year 1950. As the ^{14}C content of samples reduces in time simultaneously with the standard material, any comparison between the two results in a ^{14}C content valid for the year 1950 (= t_0).

The consequence is that an absolute activity, resulting from a ^{14}C analysis that is based on a comparison with the Oxalic Acid standard, is valid for the year 1950, irrespective of the time of measurement:

$$^{14}a \times 0.226 = {}^{14}A^0$$

The original value of the decay constant λ is $1/8033$ a^{-1} (Libby 1952), based on a half-life of 5568 a; $T_{1/2}$ of ^{14}C was later corrected to 5730 a (Godwin 1962), resulting in a decay constant of $1/8267$ a^{-1} (see our later discussion with the examples in section 3).

1.3. Definition of the ^{14}C Standard Activity

We can now define the *standard activity* as 95% of the activity of the specific batch of Oxalic Acid nr 1 in AD 1950 (in S&P77 defined as A_{ABS}):

$$^{14}A_{RN}^0 = 0.95 \ {}^{14}A_{Ox1N}^0 = 13.56 \pm 0.07 \ \text{dpm}/\text{gC} = 0.226 \pm 0.001 \ \text{Bq}/\text{gC} \quad , \tag{6}$$

where R stands for "Reference", N for "Normalized" for isotope fractionation (to $^{13}\delta = -25‰$, except in the case of Ox1 to $^{13}\delta = -19‰$) and dpm/gC means disintegrations per minute per gram of carbon, while the superscript ^{0} refers to the fact that the definition is valid for the year 1950 only.

The definition presented by Equation 6 is related to time by

$$^{14}A_{RN} = {}^{14}A_{RN}^0 \ e^{-\lambda(t_i - t_0)} = 0.95 \ {}^{14}A_{Ox1N}^0 e^{-\lambda(t_i - t_0)} = 0.95 \ {}^{14}A_{Ox1N} \quad , \tag{7}$$

where t_0 and t_i refer to the year 1950 and to the moment of the origin of the sample, respectively; in other words, $t_i - t_0$ is the true age of the sample. Here S&P77 use the symbol A_{ON}.

Because the original supply of oxalic acid has been exhausted, a new batch of oxalic acid (Ox2) is available for distribution by the NIST (formerly US-NBS).

Through careful measurement by a number of laboratories (Mann 1983), the ^{14}C activity was related to that of the original Ox1 by

$$^{14}A^0_{Ox2N} = (1.2736 \pm 0.0004) \; ^{14}A^0_{Ox1N} \; . \tag{8}$$

Contrary to the Old Oxalic acid (with a true $^{13}\delta$ value of -19.2 ‰, H Craig, personal communication; Mann 1983), the New Oxalic acid (with $^{13}\delta_{Ox2} = -17.6‰$) is to be normalized (= corrected for isotope fractionation) to $^{13}\delta = -25‰$, while both activities refer to AD 1950.

All $^{13}\delta$ values are with respect to the VPDB standard (Gonfiantini 1984).

Consequently the standard activity is

$$^{14}A^0_{RN} = \frac{0.95}{1.2736} = 0.7459 \; ^{14}A^0_{Ox2N} \quad \text{or} \quad ^{14}A_{RN} = 0.7459 \; ^{14}A_{Ox2N} \; , \tag{9}$$

where the $^{14}A^0$ values for Ox1 and Ox2 refer to the activity of the material in 1950, irrespective of the time of measurement.

2. FINAL DEFINITIONS

We can now more carefully specify the ^{14}C content of a sample in terms of the *activity ratio* or *concentration ratio* as the ratio between the measured ^{14}C content and the value of the standard (which always has to be normalized for $^{13}\delta$), with both terms referring to the time of measurement, as mentioned in Equation 2:

$$^{14}a = \frac{^{14}A}{^{14}A_{RN}} = \frac{^{14}A^0 e^{-\lambda(t_m - t_0)}}{^{14}A^0_{RN} e^{-\lambda(t_m - t_0)}} = \frac{^{14}A^0}{^{14}A^0_{RN}} = \;^{14}a^0 \; , \tag{10}$$

where t_0 refers to the year 1950, ^{14}A is the activity of the sample measured at time t_m, and $^{14}A_{RN}$ (= $0.95 ^{14}A_{Ox1}$ with $^{13}\delta_N = -19‰$ or $0.746 ^{14}A_{Ox2}$ with $^{13}\delta_N = -25‰$) is the value of the standard determined with the same detection efficiency, at about the same time t_m and corrected for isotope fractionation. In this way ^{14}a results from different laboratories become comparable. The decay of sample and standard ^{14}C content from t_0 to t_m is described by Equation 5. S&P77 do not use a specific symbol for ^{14}a and refer to this as A_S/A_{ON}.

Again it should be emphasized that the consequence of the relative measurement is that the resulting value of ^{14}a is independent of the year of measurement (see §1.2).

As was anticipated above, certain studies of natural systems are concerned with only small differences in ^{14}C content. In those cases it is conventional to report ^{14}C data as the relative difference between the measured sample activity and that of the reference:

$$^{14}\delta = \frac{^{14}A}{^{14}A_R} - 1 = \frac{^{14}A^0}{^{14}A^0_R} - 1 = \;^{14}a - 1 \; . \tag{11}$$

Here, as usual, the δ value is a small number and is therefore reported in ‰ ($\equiv 10^{-3}$). (See the related remarks following Equation 3.)

The $^{14}\delta$ values are quoted by S&P77 as $d^{14}C$.

As mentioned, it has become common practice to normalize ^{14}C results for deviations of the measured $^{13}\delta$ from -25‰. Now the discussion of the normalization procedure can be completed. Since conventionally $^{13}C/^{12}C$ values are related to the international standard for stable isotopes, Vienna PDB, Equation 4 can be rewritten as

$$\frac{^{14}A_N / {}^{14}A_{RN}}{^{14}A / {}^{14}A_{RN}} = \left[\frac{^{13}R_N / {}^{13}R_{VPDB}}{^{13}R / {}^{13}R_{VPDB}} \right]^2 ,$$

or using Equation 10, with $^{13}\delta_N = -25$‰, and consequently $1 + {}^{13}\delta_N = 0.975$:

$$^{14}a_N = {}^{14}a \left[\frac{1 + {}^{13}\delta_N}{1 + {}^{13}\delta} \right]^2 = {}^{14}a \left[\frac{0.975}{1 + {}^{13}\delta} \right]^2 , \tag{12}$$

(in S&P77 referred to as A_{SN}/A_{ON}), and likewise

$$^{14}A_N = {}^{14}A \left[\frac{0.975}{1 + {}^{13}\delta} \right]^2 \tag{13}$$

(in S&P77 referred to as A_{SN}), while Equation 11 transforms into

$$^{14}\delta_N = {}^{14}a_N - 1 , \tag{14}$$

in S&P77 indicated by $D^{14}C$.

3. EXAMPLES

In general, the presentation of ^{14}C results depends on the type of application. After each formal treatment we will present some realistic examples to illustrate the applicable definitions and equations.

3.1. Enhanced ^{14}C Radioactivity (nuclear industry, biomedical research)

In studies on the extent of radioactive contamination, for instance by ^{14}C, the absolute radioactivity of the sample is required. Consequently the result of the routine ^{14}C measurement, in this case the ^{14}a value, has to be converted back to the absolute value by

$$^{14}A = {}^{14}a \times 13.56 \ (dpm/gC) = {}^{14}a \times 0.226 \ (Bq/gC) . \tag{15}$$

The absolute activity obtained by multiplying ^{14}a by 0.226 is valid for the year 1950 (see Equation 10). In fact, it has to be corrected for radioactive decay of the standard from 1950 (t_0) to the year of sampling (t_s). Moreover, the activity in this case is not to be normalized. If the laboratory provides only normalized values, $^{14}a_N$, these have to be "de-normalized" as shown in Equation 16.

We can now meet our commitment to give the equation for the radioactivity at the time of sampling ($^{14}A^S$) and for de-normalization by applying Equations 6, 10, 12 and 15:

$$^{14}A^S = {}^{14}a_N^0 \left(\frac{1 + {}^{13}\delta}{0.975} \right)^2 e^{-\lambda(t_s - t_0)} \; {}^{14}A_{RN}^0$$

$$= {}^{14}a_N \left(\frac{1 + {}^{13}\delta}{0.975} \right)^2 e^{-(t_s - 1950)/8267} \times 0.226 \, (\mathrm{Bq}/\mathrm{gC}) \; , .$$

(16)

where t_0 and $^{14}a^0$ both refer to AD 1950, and t_s and A^S to the year of sampling; λ is based on the true ^{14}C half-life of 5730 yr; $^{14}a_N$ is the routinely acquired (normalized) ^{14}C content of the sample.

Example: Insect from Chernobyl

The AMS-measured ^{14}C concentration ratio is

$$^{14}a_N = 1.7172 \;\; \text{or} \; = 171.72 \, \% \; .$$

The $^{13}\delta$ analysis obtained in the AMS system resulted in

$$^{13}\delta = -34.8 \, \%o \; .$$

This unusual value is due to the fact that the original sample—because of its expectedly high ^{14}C content—was not processed in the routine combustion system, instead being carbonized to provide an amorphous carbon sample. In the accelerator this behaves differently from the routine samples, resulting in a relatively weak ^{13}C ion beam.

The $^{14}a_N$ value routinely obtained now has to be de-normalized according to

$$^{14}a = {}^{14}a_N \, [(1 + {}^{13}\delta) / 0.975]^2 = 1.6829 \;\; \text{or} \; = 168.29 \, \% \; . \qquad \text{[cf. Eq 12]}$$

The absolute activity in the year 1950 would have been

$$^{14}A^0 = {}^{14}a^0 \times 0.226 = {}^{14}a \times 0.226 = 0.380 \, \mathrm{Bq/gC} \; . \qquad \text{[cf. Eq 15]}$$

This value has to be corrected for radioactive decay of the standard to the year of sampling $t_s = 1986$:

$$^{14}A^S = {}^{14}A^0 \exp[-(1986 - 1950) / 8267] = 0.379 \, \mathrm{Bq/gC} \; . \qquad \text{[cf. Eq 16]}$$

3.2. Hydrology

From a geochemical point of view, the use of $^{14}a^S$, the non-normalized ^{14}C content at the time of sampling, is more meaningful than a δ value. Instead of applying a normalization correction, the initial ^{14}C content of groundwater is approximated based on specific geochemical inference of the origin of the inorganic carbon content. Furthermore, if we are dealing with groundwater ages, it is irrelevant—from a hydrological point of view—whether ages count back in time from the year of sampling (calculation based on $^{14}a^S$) or from 1950 (calculation based on $^{14}a = {}^{14}a^0$). Moreover, the precision of routine ^{14}C dating is ±50 yr or more in any case. Consequently, we can equally well use the simplest ^{14}a value in % as is obtained in basic laboratory procedures.

Without ^{13}C normalization, the activity ratio in the year of sampling is

$$^{14}a^S = {}^{14}a_N \left(\frac{1 + {}^{13}\delta}{0.975} \right)^2 e^{-(t_s - 1950)/8267} \; .$$

(17)

in S&P77 indicated by A_S/A_{ABS}.

Often these values are given in percent of modern carbon (pMC or pmc) or percent modern (pM). In addition, pM/100 (= $^{14}a^s$) is sometimes called "fraction modern". However, the symbol pM is used by water chemists and oceanographers to mean picoMole. Therefore, pmc, pMC, pM, and similar variants should not be used: % **is adequate in combination with a well-defined symbol.**

Example: Groundwater

The measured and normalized activity or concentration ratio is

$$^{14}a_N = 0.537 = 53.7 \% .$$

The measured $^{13}\delta$ value of the total carbon content (as obtained by the extraction procedure) is

$$^{13}\delta = -13.82 \%o .$$

In groundwater hydrology we are interested in the ^{14}C content of the water sample at the time of sample collection. Therefore, the ^{14}a value has to be de-normalized:

$$^{14}a = {}^{14}a_N [(1 + {}^{13}\delta) / 0.975]^2 = 0.549 = 54.9 \% . \qquad \text{[cf. Eq 12]}$$

The ^{14}C content in the year of sampling (1998) then is

$$^{14}a^S = {}^{14}a_N [(1 + {}^{13}\delta) / 0.975]^2 \ exp[-(1998 - 1950) / 8267] = 0.546 = 54.6 \%$$
$$(\equiv 54.6 \ pmc \ (or \ pMC) = \% \ of \ modern \ carbon) . \qquad \text{[cf. Eq 17]}$$

Using more or less sophisticated models, the ^{14}C and the ^{13}C data, together with information on the chemical composition of the water sample, can be used to estimate the sample age (i.e. the period of time since the infiltration of the water). A straightforward "water age" as obtained by simply applying Equation 24 is not possible.

3.3. Oceanography and Atmospheric Research

The same equation holds for the oceanographic applications. However, as the spread of the data generally is quite small, it is common practice to report the ^{14}C data as relative numbers, in other words, as decay-corrected $^{14}\delta$ values:

$$^{14}\delta^S = {}^{14}a^S - 1 = \frac{^{14}A}{^{14}A_{RN}^0} - 1 . \qquad\qquad 18$$

In general, results are also corrected for isotope fractionation (= normalized):

$$^{14}\delta_N^S = {}^{14}a_N^S - 1 = {}^{14}a \cdot e^{-(t_s - t_0)/8267} \left(\frac{0.975}{1 + {}^{13}\delta} \right)^2 - 1 . \qquad (19)$$

This symbol is equivalent to $\Delta^{14}C$ as defined by S&P77.

These equations are used to express the ^{14}C content of samples of ocean water as well as of atmospheric CO_2.

Again we must stress that a δ value is generally written in terms of ‰ and is therefore a small number. In equations it should thus **not** be written as $^{14}\delta/10^3$.

Example: Oceanic DIC and Atmospheric CO_2

The ^{14}C content resulting from a routine measurement includes normalization to $^{13}\delta = -25‰$, as follows.

1. Deep-ocean bottom water DIC (=dissolved inorganic carbon)

$$\text{with } {}^{14}a_N = {}^{14}a_N{}^0 = 0.872 = 87.2\% \ . \qquad\qquad \text{[cf. Eq 10]}$$

$$\text{and: } {}^{14}\delta_N = {}^{14}a_N - 1 = -0.128 = -128‰ \ , \qquad\qquad \text{[cf. Eq 14]}$$

$$\text{with } {}^{13}\delta = +1.55\ ‰ \ .$$

When corrected for the fact that the resulting ^{14}C content is valid for the year 1950 instead of the year of sampling (1990):

$$
\begin{aligned}
{}^{14}\delta_N^S &= {}^{14}a_N \ \exp[-(1990-1950)/8267]-1 = -0.132 = -132\% \\
&\equiv \Delta^{14}C \ \ (S\&P77) \ .
\end{aligned}
\qquad \text{[cf. Eq 19]}
$$

2. Atmospheric CO_2

$$\text{with } {}^{14}\delta_N = {}^{14}a_N - 1 = 0.253 = +253\ ‰ \ , \qquad\qquad \text{[cf. Eq 14]}$$

$$\text{with } {}^{13}\delta = -7.96\ ‰ \ .$$

When corrected for the fact that the resulting ^{14}C content is valid for the year 1950 instead of the year of sampling (1985):

$$
\begin{aligned}
{}^{14}\delta_N^S &= {}^{14}a_N \ \exp[-(1985-1950)/8267]-1 = 0.247 = +247 \\
&\equiv \Delta^{14}C \ \ (S\&P77) \ .
\end{aligned}
\qquad \text{[cf. Eq 19]}
$$

With atmospheric CO_2 samples it remains problematic whether the ^{13}C correction applied (according to Equation 12) is correct. The measured $^{13}\delta$ value may very well be affected by the admixture of biospheric or fossil-fuel CO_2, instead of by isotope fractionation alone, as is the presumption—not necessarily valid—of the correction procedure (Mook 1980).

3.4. Geochemistry

In geochemical studies it is often necessary to know the original ^{14}C content of a sample in the year of the sample origin t_i (such as the year a tree ring was formed), instead of the activity in 1950, as is routinely obtained. As the measured ^{14}C content (activity or concentration) is valid for the year 1950, it has to be corrected for radioactive decay from the year of origin (t_i) to 1950,

$$
{}^{14}A^i = {}^{14}A^0 \ e^{-(t_i - 1950)/8267} \ , \tag{20}
$$

and equally for the normalized values:

$$
{}^{14}A_N^i = {}^{14}A_N^0 \ e^{-(t_i - 1950)/8267} \ . \tag{21}
$$

For this correction again the "correct" half-life of ^{14}C (5730 a) must be used with $\lambda = 1/8267$ a^{-1}. Furthermore, $^{14}A^0$ and $^{14}a^0$ refer to 1950 and $^{14}A^i$ and $^{14}a^i$ to the year of the origin of the carbon containing sample material.

Finally the relations for ^{14}a and $^{14}\delta$ can be established. For the normalized and age corrected values we can now write

$$^{14}\delta^i = {}^{14}a^i - 1 = \frac{^{14}A^i}{^{14}A_{RN}^0} - 1$$

$$= \frac{^{14}A^0 \; e^{-(t_i - 1950)/8267}}{^{14}A_{RN}^0} - 1 = {}^{14}a \cdot e^{-(t_i - 1950)/8267} - 1 \; , \tag{22}$$

equivalent to $\delta^{14}C$ in S&P77, and for the normalized values,

$$^{14}\delta_N^i = {}^{14}a_N^i - 1 = {}^{14}a \cdot e^{-(t_i - 1950)/8267} \left(\frac{0.975}{1+^{13}\delta} \right)^2 - 1 \; , \tag{23}$$

equivalent to Δ in S&P77.

Example: Atmospheric ^{14}C Content from a Known-Age Sample: Wood from a Tree Ring

The measured activity ratio, that is, the activity with respect to 0.95 times the measured and normalized oxalic acid activity, is

$$^{14}a = {}^{14}a^0 = ({}^{14}A / {}^{14}A_{RN}) = 0.4235 \quad \text{or} \quad = 42.35 \; \% \; . \qquad \text{[cf. Eq 10]}$$

The measured $^{13}\delta$ of the sample:

$$^{13}\delta = -22.5 \; \%_o \; .$$

The normalized activity ratio of the sample is

$$^{14}a_N = {}^{14}a \; [0.975 / (1 - 0.0225)]^2 = 0.4213 \quad \text{or} \quad = 42.13 \; \% \; . \qquad \text{[cf. Eq 12]}$$

Using the normalized, age-corrected ^{14}a value calculated above, the conventional ^{14}C age is

$$T = -8033 \; \ln \; {}^{14}a_N = 6943 \; BP \; . \qquad \text{[cf. Eq 24]}$$

The normalized relative activity is

$$^{14}\delta_N = {}^{14}a_N - 1 = -0.5787 \quad \text{or} \quad = -578.7 \; \%_o \; . \qquad \text{[cf. Eq 14]}$$

Suppose the tree ring is dated dendrochronologically to 5735 cal BC, i.e. $t_i = -5735$ a.

The age-corrected, i.e. the original, ^{14}C content of the sample is then

$$^{14}\delta_N^i = {}^{14}a_N^i - 1 = {}^{14}a_N \; \exp[-(-5735 - 1950)/8267] - 1$$
$$= 0.0674(5) \quad \text{or} \quad = +67.4(5) \qquad (\equiv \Delta^{14}C \; \text{defined by S \& P77}) \; . \qquad \text{[cf. Eq 23]}$$

3.5. ^{14}C Ages

In geological and archeological dating, ages are based on the normalized $^{14}a_N$ (to $^{13}\delta = -25‰$) and on a half-life of 5568 yr, and are calculated by applying

$$\text{Conventional age} = -8033 \ln {}^{14}a_N \ . \tag{24}$$

This defines the ^{14}C time scale in years BP (Before Present, i.e. AD 1950). This time scale needs to be calibrated in order to obtain historical ages (cal AD, cal BC, cal BP). For the calibration procedures and conventions we refer to the special Calibration Issues published by *Radiocarbon* (the most recent is Stuiver and Van der Plicht 1998).

4. SUMMARY

The interrelation between the various definitions and symbols, and their validity over the time scale, is illustrated by Figure 1. In Table 1 all symbols used are classified and compared to the symbols used by S&P77.

$^{14}A^i$	$^{14}A^0$	$^{14}A^s$
$^{14}a^i$	$^{14}a^0 = {}^{14}a$	$^{14}a^s$
$^{14}\delta^i (\equiv \delta^{14}C)$	$^{14}\delta^0 = {}^{14}\delta (\equiv d^{14}C)$	$^{14}\delta^s$

◄━━━━ past   AD 1950   present   future ━━━━►

$^{14}A^i_N$	$^{14}A^0_N$ and $^{14}A^0_{RN}$	$^{14}A^s_N$
$^{14}a^i_N$	$^{14}a^0_N = {}^{14}a_N$	$^{14}a^s_N$
$^{14}\delta^i_N (\equiv \Delta)$	$^{14}\delta^0_N = {}^{14}\delta_N (\equiv D^{14}C)$	$^{14}\delta^s_N (\equiv \Delta^{14}C)$

Figure 1 Illustration of the definition of symbols for reporting ^{14}C data along the time scale from the past (for the data to be corrected for age/decay), via the year 1950 to the time of sample collection(s) and the future. Above the line are the non-normalized data (not corrected for isotope fractionation); below are the the normalized values. The bold symbols are defined in this paper, the non-bold (in parentheses) were defined in S&P77.

Symbols stand for:

A = absolute activity or concentration

a = activity/concentration ratio to standard

δ = relative ^{14}C content (i.e. deviation of activity or concentration from standard)

Super- and subscripts stand for:

N = normalized

0 = time zero $\equiv$ AD 1950

i = initial $\equiv$ time of growth/formation

s = time of sampling

5. CONCLUDING REMARKS

In this paper we try to clarify definitions and symbols used in presenting results from ^{14}C analyses on a variety of materials, obtained by a variety of analytical instrumentation. In the past, basic agreements were reached at the International Radiocarbon Conferences, in particular concerning the use of reference materials (standards), the adoption of a standard activity, the application of the "wrong" and the "right" ^{14}C half-life, and the correction for isotope fractionation. The rapid spread of ^{14}C applications throughout a variety of disciplines has sometimes led to the introduction of personal or ad hoc definitions, resulting in considerable confusion. Because a few practical symbols were lack-

Table 1 Review of the symbols used in reporting ^{14}C activities. The upper symbol is defined in this paper. The symbols in the shaded areas refer to S&P77 (Stuiver and Polach 1977). In the 3rd column the symbols apply to the decay-corrected values, i.e. corrected for decay of the sample activity from 1950 to the year of sampling (Equations 17–18). The symbols in the 6th column refer to Equations 21–23. The superscript 0 assigns the value to the year 1950.

	Measured at t_0 (1950); a and δ at any time	Normalized	Decay-corrected to sampling at t_S	Decay-corrected and normalized	Age-corrected from origin at t_i	Age-corrected and normalized
Absolute ^{14}C content of sample	$^{14}A^0$	$^{14}A_N$	$^{14}A^S$	$^{14}A_N^S$	$^{14}A^i$	$^{14}A_N^i$
	A_S	A_{SN}				
Absolute ^{14}C content of standard	$^{14}A_R^0$	$^{14}A_{RN}$		$^{14}A_{RN}^0$		
		A_{ON}		A_{ABS}		
^{14}C abundance ratio	$^{14}a = {}^{14}a^0$	$^{14}a_N$	$^{14}a^S$	$^{14}a_N^S$	$^{14}a^i$	$^{14}a_N^i$
	A_S/A_{ON}	A_{SN}/A_{ON}	A_S/A_{ABS}	A_{SN}/A_{ABS}		
Relative ^{14}C content	$^{14}\delta = {}^{14}\delta^0$	$^{14}\delta_N$	$^{14}\delta^S$	$^{14}\delta_N^S$	$^{14}\delta^i$	$^{14}\delta_N^i$
	$d^{14}C$	$D^{14}C$	$\delta^{14}C$ [1]	$\Delta^{14}C$ [2]	$\delta^{14}C$ [3]	Δ [4]

The upper symbols in each block are defined by their sub- and superscripts. The S&P77 symbols are shown in the shaded areas. They refer to the following fields of study:

[1] in hydrology the use of the ^{14}a value (or rather $^{14}a^S$) is more common (no specific symbol proposed by S&P77)
[2] in oceanography and atmospheric studies
[3] in geochemical studies if age correction is possible
[4] idem, such as past ^{14}C variations from tree rings

ing, the strange habit arose of having physical quantities defined or recognized by the "units" that accompany numerical results. Examples of this are the introduction of pM, pmc, or pMC.

We have introduced several new "rational" symbols, based on A (radioactivity), a (activity ratio or concentration ratio), and δ (relative difference in activity or concentration), provided with a limited number of super- and subscripts. These are proposed to replace symbols such as $d^{14}C$, $D^{14}C$, $\delta^{14}C$, $\Delta^{14}C$, and Δ. For practical reasons, reference in the symbols to ^{14}C is made by prefixing the superscript "14" as in "^{14}C" itself. Rather than indulging ourselves with the expectation that the ^{14}C community will now immediately adopt our propositions, we hope that this paper will at least contribute to a better understanding of the complicated matter of reporting ^{14}C results, and perhaps form the basis for a new, uniform notational system in the various disciplines that rely on ^{14}C data.

As confusion still exists concerning "relative" and "absolute" pM and pmc or pMC, we note that:

1. Their definition is not unique;
2. They interfere with the definition of pM as picoMole ($= 10^{-12}$ mole) used in water chemistry and oceanography as the unit for tracer concentrations (in picoMole/liter);
3. Their use is not needed.

Accordingly, we recommend that the use of pM (and preferably also of pmc or pMC) be abandoned completely, and that we restrict ourselves to the use of % (equivalent to 10^{-2}, Equation 2) and ‰ (equivalent to 10^{-3}, Equation 3), in combination with the proper symbols.

Finally, we summarize the most relevant equations to clarify the systematics of our presentation.

Measurement:

$$\frac{\text{standardized net counting rate sample}}{\text{standardized net counting rate Ox1 or Ox2}} = {}^{14}a$$

	Sample	**Reference/Standard**

Absolute activity
at time of measurement t_m:

$${}^{14}A \qquad\qquad {}^{14}A_R$$

Normalization for fractionation:

$${}^{14}A_N = {}^{14}A\left[\frac{0.975}{1+{}^{13}\delta}\right]^2 \qquad\qquad {}^{14}A_{Ox1N} = {}^{14}A_{Ox1}\left(\frac{0.981}{1+{}^{13}\delta}\right)^2$$

$${}^{14}A_{Ox2N} = {}^{14}A_{Ox2}\left(\frac{0.975}{1+{}^{13}\delta}\right)^2$$

Correction to 1950 = t_0:

$${}^{14}A^0 = {}^{14}Ae^{\lambda(t_m-1950)} \qquad\qquad {}^{14}A_R^0 = {}^{14}A_Re^{\lambda(t_m-1950)}$$

$${}^{14}A_N^0 = {}^{14}A_Ne^{\lambda(t_m-1950)} \qquad\qquad {}^{14}A_{RN}^0 = {}^{14}A_{RN}e^{\lambda(t_m-1950)}$$

Standard activity:

$${}^{14}A_{RN}^0 = 0.95\ {}^{14}A_{Ox1N}^0 = 0.7459\ {}^{14}A_{Ox2N}^0 = 13.56\ \text{dpm}/\text{gC}$$

Measurement (result independent of time of measurement):

$$\frac{\text{net standardized CR of sample}}{\text{net standardized CR of Ox1}} = {}^{14}a = {}^{14}a^0$$

automatically valid for
1950:

$${}^{14}a \times 13.56\ \text{dpm}/\text{gC} = {}^{14}A^0$$

	Not normalized	**Normalized**

Corrected to time of sampling t_s:

$${}^{14}A^S = {}^{14}Ae^{-\lambda(t_s-1950)} \qquad\qquad {}^{14}A_N^S = {}^{14}A_Ne^{-\lambda(t_s-1950)}$$

Corrected to time of sample origin t_i:

$${}^{14}A^i = {}^{14}Ae^{-\lambda(t_i-1950)} \qquad\qquad {}^{14}A_N^i = {}^{14}A_Ne^{-\lambda(t_i-1950)}$$

Activity/concentration ratio:

$$^{14}a = \frac{^{14}A}{^{14}A_{RN}} = \frac{^{14}A^0}{^{14}A_{RN}^0} = {}^{14}a^0 \qquad\qquad {}^{14}a_N = \frac{^{14}A_N}{^{14}A_{RN}} = \frac{^{14}A_N^0}{^{14}A_{RN}^0} = {}^{14}a_N^0$$

Corrected to t_s and t_i:

$$^{14}a^S = {}^{14}a\ e^{-\lambda(t_S-1950)} \qquad\qquad {}^{14}a_N^S = {}^{14}a\left(\frac{0.975}{1+{}^{13}\delta}\right)^2 e^{-\lambda(t_S-1950)}$$

$$^{14}a^i = {}^{14}a\ e^{-\lambda(t_i-1950)} \qquad\qquad {}^{14}a_N^i = {}^{14}a\left(\frac{0.975}{1+{}^{13}\delta}\right)^2 e^{-\lambda(t_i-1950)}$$

Absolute activity at time of sampling to be obtained from:

$$^{14}A^S = {}^{14}a^S \times {}^{14}A_{RN}^0 = {}^{14}a^S \times 13.56\ \ dpm/gC$$

Relative ^{14}C Content (i.e. deviation from standard):

$$^{14}\delta = {}^{14}a - 1 \qquad\qquad\qquad {}^{14}\delta_N = {}^{14}a_N - 1$$

As measured valid for 1950:

$$^{14}\delta^0 = {}^{14}\delta$$

Corrected to t_s and t_i:

$$^{14}\delta^S = {}^{14}a^S - 1 = {}^{14}a\ e^{-\lambda(t_S-1950)} - 1$$

$$^{14}\delta^i = \qquad = {}^{14}a\ e^{-\lambda(t_i-1950)} - 1$$

$$^{14}\delta_N^S = \qquad = {}^{14}a^S\ e^{-\lambda(t_S-1950)} - 1 = {}^{14}a\left(\frac{0.975}{1+{}^{13}\delta}\right)^2 e^{-\lambda(t_S-1950)} - 1$$

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