

CONFERENCE PAPER

Fading of the ^{14}C bomb peak – students’ project to observe the Suess effect

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Received: 18 February 2025; **Revised:** 20 May 2025; **Accepted:** 08 June 2025

Abstract

The natural variability of atmospheric ^{14}C has been significantly altered by anthropogenic activities linked to technological advancements and energy consumption over the past two and a half centuries. The Suess effect, a consequence of the combustion of old carbon (fossil fuels) since the mid-18th century and the bomb peak from the mid-20th century’s thermonuclear tests, has obscured the natural ^{14}C signal in the atmosphere. This study presents a ^{14}C analysis of leaves, flowers, and grass collected from various locations worldwide. Over the last 10 years, more than 150 samples have been collected and used as materials for experiments conducted by students in physics lab classes (Department of Physics, ETH Zurich) or as part of school projects. Short-lived vegetal fragments are ideal material for teaching radiocarbon dating and demonstrating our research. The collection of data presented here underscores the sensitivity of radiocarbon analysis for detecting fossil carbon components. Trees from urban sites worldwide demonstrate a dilution of the atmospheric ^{14}C concentration of 2–3%. Trees growing close to busy roads and traffic show a dilution of up to 10%. Moreover, the data show a fading trend of the bomb peak observed from 2015 to the present, as well as the direct impact of fossil CO_2 on the ^{14}C concentration of the living biota around us.

Introduction

About the bomb peak and the Suess effect

The natural variability of atmospheric ^{14}C necessitates calibration and can affect the precision of the calendar ages. The radiocarbon time scale is punctuated by periods of such an imprecise ^{14}C clock (for example, the Younger Dryas period). However, natural changes have no comparison to the anthropogenic impact on the atmospheric ^{14}C during the last 250 years. Although humans have shaped their surrounding environment for millennia, the unprecedented changes to the Earth System (Syvitski et al. 2020) have their roots in the Industrial Revolution. The shift to fossil carbon as the source of energy has disturbed the atmospheric ^{14}C content. In 1955, Suess documented this by measuring the annual rings from the last 300 years (Suess 1955). His observation was possible thanks to the tree rings, which recorded the annual conditions over millennia. The second anthropogenic impact on atmospheric ^{14}C was underway during his study. The series of above-ground thermonuclear explosion tests followed the Ivy Mike detonation on Elugelab (“Flora”) Island, Enewetak Atoll, in the morning (local time) on November 1, 1952 (Zander and Araskog 1973; Bergkvist and Ferm 2000). The intensity of tests reached its highest point in 1963, shortly before the partial ban was signed in November of that year. Interestingly, Rafter and Fergusson, who established a radiocarbon laboratory in New Zealand (see Turnbull et al. 2021), were the first to observe

the bomb peak ^{14}C in the Southern Hemisphere (Rafter and Fergusson, 1957). The follow-up measurements and new applications of the ^{14}C spike have been established in various research fields. As summarized by Kutschera (Kutschera 2022) and others (e.g., Nydal and Gislefoss 1996; Horvitz and Sternberg 1999; Levin and Hesshaimer 2000; Wild et al. 2000; Geyh 2001; Fedi et al. 2013; Handlos et al. 2018; Hajdas et al. 2019, 2021, 2022) the bomb peak as a tracer was a “silver lining” of the controversial and tragic weapon testing. The combined data sets of the bomb peak ^{14}C measurements around the globe (Nydal and Lovseth 1965; Nydal and Lövseth 1983, 1996; Hua et al. 1999, 2022) helped to achieve calendar ages for measured values of F^{14}C (Reimer et al. 2004).

Following its discovery, the fate of the bomb peak ^{14}C , its geographic distribution, and its transfer from the atmosphere to other carbon reservoirs were intensively studied (Nydal and Lovseth 1965, 1970). The ocean absorbed a large portion of the bomb peak; however, fossil fuel CO_2 emissions, which continue to rise, led to a lower atmospheric $^{14}\text{C}/^{12}\text{C}$ ratio. The observations were made in highly polluted (high CO_2 emissions) urban areas (Levin et al. 2003, 2008, 2013), but it was also predicted that the Suess effect would eventually overprint the global bomb peak signal (Levin et al. 2010). The case of the fading bomb peak gained a wider audience after publication by Graven (2015) and even received some media attention. Many users and collaborators asked questions about the future of radiocarbon dating. Indeed, the predicted change of atmospheric ^{14}C is closely related to the current and near-future emissions of fossil fuel CO_2 . If the emissions remain high, the green plants and animals living at the end of this century will be depleted in ^{14}C to a magnitude that measured F^{14}C will be around 0.8, compared to the pre-anthropogenic value $\text{F}^{14}\text{C} = 1$. Such development poses problems for future research in forensics, art, and archeology.

Monitoring of the atmospheric ^{14}C in the atmosphere around the globe has been performed since the 1960s), and decades of efforts (Turnbull et al. 2017; Seiler et al. 2023) have resulted in a network of instrumental data collection (Wang et al. 2018). The collection of atmospheric CO_2 for the subsequent ^{14}C analysis has undergone technical development (Gautschi 2017), but it still requires organizational efforts. In contrast, as demonstrated by studies on trees (Hua et al. 2003) and recent research on leaves and grass (Varga et al. 2019, 2020), vegetation provides a straightforward method for collecting data, even in the most remote regions.

The publication by Graven (2015) coincided with an ongoing school project that focused on the bomb peak ^{14}C signal in leaves of trees from the surroundings. So far, this education project has been going on for more than 10 years and has involved high school and ETH students (physics lab). The primary goal is to observe the local changes in ^{14}C (ETH, Zurich) and at remote geographic locations. The second goal is to allow laboratory involvement in teaching. Additionally, these data can support research projects where the local ^{14}C signal is relevant. The dataset documents the transition from the bomb peak elevated atmospheric ^{14}C to the ^{14}C -depleted atmosphere.

Methods

Sites and samples

The choice of samples was arbitrary and related to opportunities to collect the leaves (home location, travel). Students and colleagues were asked to document the location of the samples. Over the years, one of the authors (IH) has collected leaves from the same trees. A map, prepared to the best of our knowledge (Figure 1), shows the locations of the sites. Three locations in Zurich and nearby regions have the highest number of samples. A couple of trees were sampled annually or biannually. The sites included trees at (1) an urban Zurich (409 m a.s.l.) with different intensities of traffic (2) a campus ETH Hönggerberg (520 m a.s.l.) located slightly above the urban Zurich and on the edge of a forest; (3) a village Boppelsen country site near Zurich (521 m a.s.l.). Locations of sites worldwide are shown on a map (Figure 1) and listed in Table S1 (supplementary). Most samples originated from Europe, but a few were also collected from other continents. For example, samples from Accra Airport (Ghana) and Faleme Valley (Senegal) were among the first to be collected for this study.



Figure 1. Google Maps shows sites where samples were collected (see the link [Leaves sampling sites](#))

Fresh annual leaves were mainly collected during their growing season. A few samples were prepared from dry leaves collected on the ground, possibly from previous growing seasons. Table 1 summarizes all the sites; details are included in the supplementary section. Figure 2 shows the two trees repeatedly sampled: Persian ironwood (*Parrotia persica*) at the campus ETH Honggerberg and a poplar tree (*Populus nigra* ‘*Italica*’) in Boppelsen (near Zurich).

¹⁴C analysis

Only the first acid step from the standard ABA treatment was applied to remove possible carbonates that might be present in dust and potentially contaminate the leaf's surface. The simplified treatment allows one to complete the treatment in one day, which is convenient when working on short (a few days) school projects, as well as for teaching physics labs. After soaking in 0.5 M HCl, 60°C for an hour, and multiple washes in MilliQ water, the leaves were freeze-dried (overnight). Dry leaves are weighed into Al – boats for combustion in an Elemental Analyzer. Samples of one milligram of carbon require approximately 3 milligrams of dry leaves to be combusted. The subsequent graphitization was completed using the AGE graphitization system (Nemec et al. 2010). The graphite was then pressed into the Al cathodes for analysis using the AMS MICADAS or LEA (Ramsperger et al. 2023; Synal et al. 2007; Wacker et al. 2010) systems. The measured ^{14}C concentration is given in F^{14}C (Reimer et al. 2004).

The fossil carbon Fraction (%fF) or dilution for the different samples was estimated using the equation shown below (after Quarta et al. 2007; Varga et al. 2019). Due to the lack of information about additional sources of carbon dioxide, such as the decomposition of organic matter, no corrections were applied.

Table 1. Overview of the number of samples from various locations (Figure 1)

Locations	Number of samples
ETH Campus, HPM	25
ETH Campus	14
Boppelsen	21
other locations (CH)	18
Europe	52
Africa	7
Asia	7
North America	4
South America	4
Australia	1

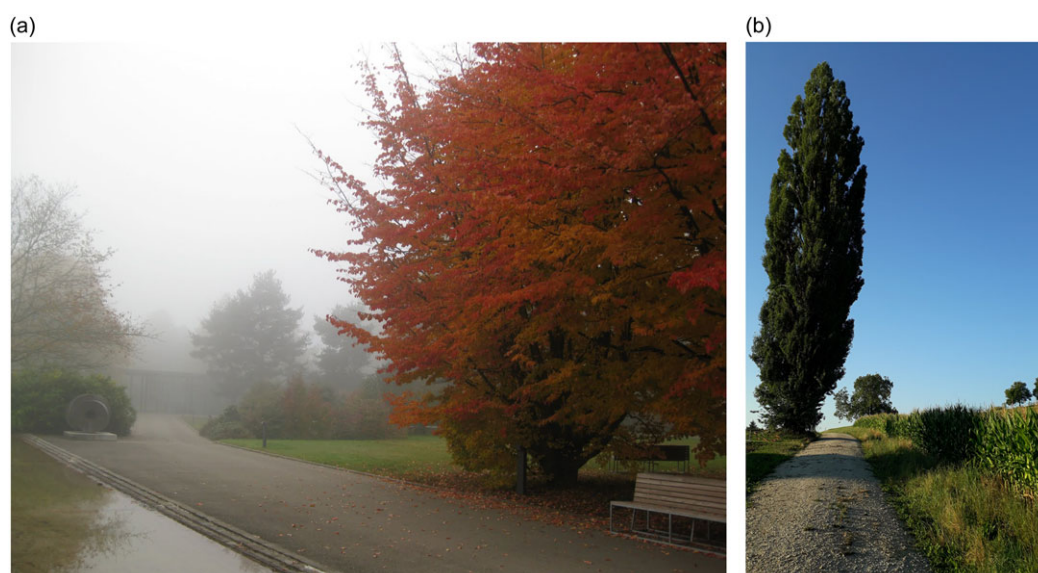


Figure 2. Pictures of two trees that were sampled multiple times in the last 10 years: (a) Persian ironwood (*Parrotia persica*) at the ETH Hoenggerberg Campus (HPM building), (b) Poplar (*Populus*) tree in Boppelsen. Leaves of corn (on the right) were also sampled and analyzed.

$$\%fF = (1 - F^{14}C_{\text{sample}} / F^{14}C_{\text{clean}}) \times 100\%$$

Here, the $F^{14}C$ sample is measured in collected leaves, grasses, and flowers, and the $F^{14}C$ clean is the annual mean value estimated by Jungfrauoch (JFJ) (Leuenberger et al. 2024). For simplicity, the JFJ site was chosen as the background site for all the samples.

Results and Discussion

Results of the AMS analysis ($F^{14}C$, with a standard precision of approximately 0.003) are reported in Table S1 (Supplementary Material). Figure 3 presents all the results in comparison to the NH1 bomb peak data (Hua et al. 2022) and supplemented by the data set from the JFJ (Leuenberger et al. 2024). The JFJ data represent a clean environment that is not polluted by local fossil carbon emission sources.

At all locations, the atmospheric ^{14}C concentration was declining, and at some locations, it reached the $F^{14}C < 1$ earlier than at others. Apparent differences can be observed between clean and urban locations, even

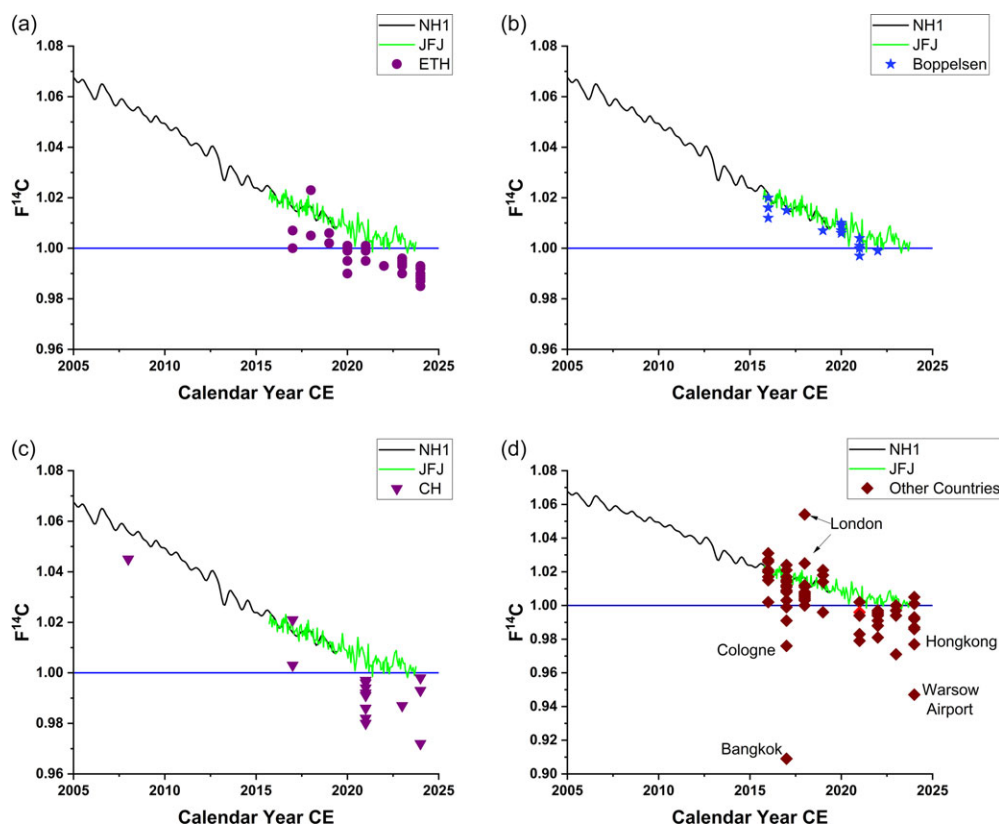


Figure 3. Results of ^{14}C analysis of leaves compared to the values for “clean air” NH1 (Hua et al. 2022) and JFJ data (Leuenberger et al. 2024): (a) ETH Zurich Campus Hoenggerberg, (b) Boppelsen (near Zurich), (c) other locations in Switzerland (CH), (d) sites around the world (see Figure 1)

within the same area, such as the Campus Science City ETH Hönggerberg (Figure 3a) and the rural region of Boppelsen (Figure 3b). Our other sites in Switzerland (Figure 3c) and around the world (Figure 3d) have a wide range of environmental cleanliness from natural remote regions (natural parks and sanctuaries) to urban areas of mega cities (Bangkok, Tokyo). Nevertheless, the observed trend of declining ^{14}C levels is present in all sites.

ETH Science City Campus Hönggerberg Zurich

The $F^{14}\text{C}$ values measured at the campus indicate the presence of fossil carbon CO_2 in the atmosphere. The campus is situated on a forested hill (520 m a.s.l.) away from traffic, resulting in relatively clean air. However, sources such as the extensive underground parking lot and the frequent bus connection are potential sources of fossil CO_2 . In addition, a contribution from the Zurich urban areas surrounding the hill contributes to the observed low atmospheric $F^{14}\text{C}$.

The values of %fF for the HPM tree fluctuate between 1 and 2%, which is comparable to other observations from urban areas (Varga et al. 2019). The grasses and flowers show a higher %fF, with the highest of 2.5% observed for a buttercup flower collected in spring 2020. The only ‘negative’ dilution values (i.e., $F^{14}\text{C}$ higher than clean JFJ air) are observed for a dry leaf (2018) collected from the ground. Other locations at the campus show a similar degree of dilution, with the lowest values at locations close to the forest (HPK building) and “Biennenkommission” the location of bee hives at the campus (Figure 4a).

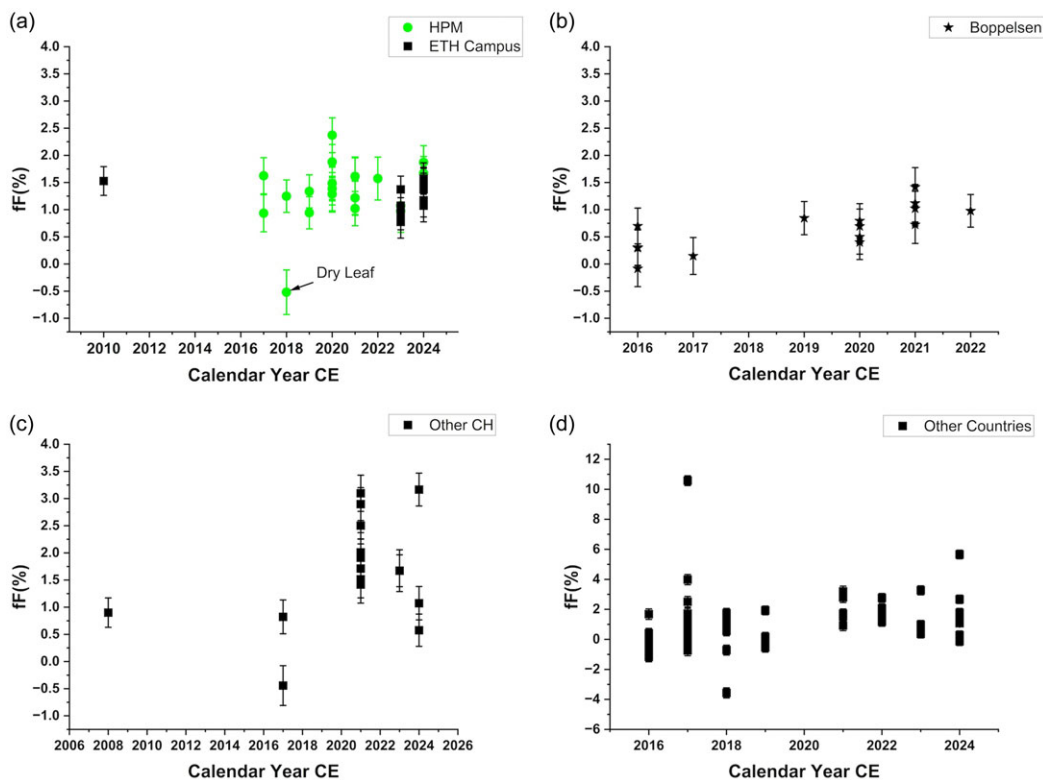


Figure 4. Fossil fuel dilution effect (%fF) based on $F^{14}C$ measured in leaves: (a) ETH Zurich Campus Hoenggerberg, (b) Boppelsen (near Zurich), (c) other locations in Switzerland (CH), (d) sites around the world (see Figure 1)

Boppelsen and other locations in Switzerland

Despite its proximity to Zurich's urban areas and surrounding industrial and traffic infrastructure, the trees and shrubs growing in the forest and fields surrounding the village exhibit a relatively low fossil fuel dilution effect. The values of %fF fluctuate between -0.4 and 1.4% (Figure 4 b). There was however one exception, leaves collected in November 2023 at the “clean” location exhibit higher dilution than in previous years.

Other locations in Switzerland show a wider range of dilution. The highest level of 2.9 – 3.1% was observed at a gas station on the highway (Sample “Wuerenlos, 2017”) and a tree growing close to a busy street in Zurich (Sample “Altstetten Lindenplatz, 2024”). Interestingly, the nearby location of Bachwissenpark in Altstetten shows a low %fF of $1.1 \pm 0.3\%$, indicating that the dilution is strongest close to the source, i.e., traffic.

High dilution is observed for a rowan berry (part of a wedding bouquet, 2008), which was most probably assembled by a local floral shop in the village of Muri (Switzerland). The ^{14}C values suggest that the rowan tree was growing close to the road or a parking space, which is, in fact, quite a common practice.

Other countries

The spectrum of samples collected worldwide is quite broad. Nevertheless, most samples were collected in Europe. The %fF values were calculated only using the continental values from Europe, which is only an estimate for the samples from the southern hemisphere. Except for two samples, Bangkok (10.5%) and Trieste (5.6%), the values of %fF fall within the range of -0.7% to 4% (Figure 4d). The very high

F¹⁴C measured for leaves collected close to Canary Wharf (London) requires additional observations because the offset from the NHZ1 values is much higher than reported for barley from Rothamsted (Dunbar et al. 2024) or Gatersleben wheat and soybean (Hüls et al. submitted 2024). Generally, the lowest %fF values were observed in rural regions that were more distant from urban centers. These observations align with previous studies (Quarta et al. 2007; Varga et al. 2019).

Records of the contemporary atmospheric ¹⁴C record

The analysis of atmospheric ¹⁴C captures the global and local effects of fossil fuel combustion. Data collected by the worldwide network confirms the growing dilution of the atmospheric ¹⁴C signal with a fossil component (Graven 2015; Hua et al. 2022). Our samples were collected in the spring and summer, and reflect values for the growing season. Therefore, most of the %fF values estimated for the leaves are attributed to pollution with fossil carbon-bearing CO₂ from the exhausts of combustion engines. As expected, urban areas with heavy traffic show high %fF values, which were also observed in other studies (Battipaglia et al. 2010; Hessel et al. 2024; Ndeye et al. 2017; Piotrowska et al. 2020; Rakowski et al. 2010). Green spaces such as urban parks help to significantly reduce the effect (e.g., Zurich Altstetten), showing that the life comfort for the population affected can be improved by consequent reduction in the use of combustion of fossil fuels and an extensive greening of the urban space.

The potential of ¹⁴C analysis in leaves and flowers

The results of this ad hoc project demonstrate the considerable potential of analyzing short-lived vegetal fragments of terrestrial plants. The simplicity of sample collection allows data to be gathered from most remote locations around the globe. Moreover, archives and collections of leaves can be utilized in future studies to expand regional data sets (Hüls et al. 2021; Hüls et al. submitted 2024). The collection of leaves and flowers can also be part of future Citizen Science projects that might help encourage communities to reduce fossil fuel combustion. In addition, the simplicity of sample preparation, combined with the modern AMS technique, allows for the flexible design of short-term projects planned according to the participant's age and knowledge. The following short description can be used when collecting leaves.

A short guide to collecting leaves for a record of atmospheric ¹⁴C

Collecting leaves or flowers for ¹⁴C analysis requires simple documentation of:

- sample name
- the datum of collection,
- the location, the geographic coordinates,
- the estimated height of the sample (optimally, 1–1.5 m above ground),
- the type (species) of the chosen tree
- (optional) a photograph of the tree and the collected leaf (leaves)

Conclusions

Radiocarbon analysis in short-lived plants and leaves has the potential to determine atmospheric ¹⁴C levels anywhere around the globe. The remote locations, such as Svalbard and Faleme Valley (Senegal), of samples collected in our project illustrate this potential. The sample collection and preparation are simple and can be completed as part of school projects that involve the local community and raise awareness about the fossil carbon dioxide released into the atmosphere. Our results align with

systematic studies conducted at other locations, which demonstrate the degree of ^{14}C concentration dilution in urban areas. Moreover, data collected regionally benefits the radiocarbon laboratories working in the region. Potential requests to estimate the degree of dilution in various samples or to provide the age of the most recent organic matter require knowledge about the local atmospheric F^{14}C .

Supplementary material. To view supplementary material for this article, please visit <https://doi.org/10.1017/RDC.2025.10140>

Acknowledgments. The project was completed with the support of the LIP team. IH thanks Mantana Maurer and Maria Belen Röttig for years of support and sample preparation. Students of ETH, the University of Basel, the University of Zurich, and the University of Bern were involved, as were pupils of several high and primary schools in Zurich and other regions of Switzerland. Many thanks to all the colleagues who collected the samples.

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