Supporting Information for

# **Dynamics of deep soil carbon – insights from 14C time-series across a climatic gradient**

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**Contents of this file:**

Tables S1-5

Figures S1-3

## **Introduction**

## This supporting information provides details on the modeling approach used in this paper, contains ancillary data and details on the estimation of petrogenic carbon.

**S1 Numerical model in Matlab Environment**

The purpose of this section is to explain the necessity of a robust numerical modelling approach for 14C time-series which can be applied ubiquitously in radiocarbon turnover estimates in oceanic and terrestrial reservoirs. **The code that can be employed to do this is freely available with this paper.** Torn et al. (2009) explains that a single measured radiocarbon value collected on the falling art of the bomb-curve yields two estimates of the turnover time. In the case of two time-points, this uncertainty is avoided and a single estimate can be produced. For this reason, time-series radiocarbon can be crucial. Graven et al. (2015) highlighted that owing to continued burning of fossil fuels, the importance of time-series measurements can only increase. In this section, we elaborate on a sensitivity analysis and error propagation analysis. The Matlab numerical optimization runs iterations until the lowest mean-squared error for both time points is reached.

### **S1.1 Necessity of numerical approach**

**SI1.1.1 General form**

The incorporation of atmospheric 14C into the any terrestrial reservoir is inherently time-dependent, and therefore as be solved numerically, as can be proven in the following manner: For the isotopic signature of any reservoir the value of a variable at can be formulated as the following:

Hererefers to the new value, refers to the previous point, is the derivative (i.e. slope) of the previous point and refers to the time-step between and . For any case of uptake of atmospheric 14CO2, the derivative can be determined:

Here, refers to the decay rate of 14C, to the turnover rate, and to the atmosperhic value of the atmosphere of year . When we combine Eq. SI.1 and Eq. SI.2. Substituting Eq. SI.1 in Eq. SI.2 gives:

Which can be rewritten as:

In this particular scenario we have annual data, so can be defined to 1, resulting in:

Which equals the Eq. 2.5 provided in Torn et al. (2009). There is an internal inherent dependency of the value of , both dependent on the atmospheric input as well as the previous timepoint, which is also dependent on . Therefore, the equation cannot be solved analytically and numerical iteration is required. In the present form, the model can be used in any case for any radiocarbon-based time-series.

**SI1.1.2 Adjustment general form to form a two-pool model**

In order to answer relevant biogeochemical questions, a multiple-pool model can be constructed (Fig. S1). Considering both sub-pools add up to the single pool, we can construct the following equation:

In Eq. 5 and 6, refers to the relative proportion of mass of the first pool and to the proportion of mass of the second pool. The refers to the turnover of the first (or fast) pool, refers to the turnover of the second (or slow) pool. This approach has been established in literature as has been shown in Baisden et al., (2002, 2013) and Prior et al., (2007). This approach requires the model to resolve three instead of a single unknown.

Implementing Eq. 5 and 6 into Eq. 4 yields:

In previous publications (e.g. Baisden et al., (2002, 2013) and Prior et al., (2007)) assumption was made either regrading to the mass distribution or to the turnover time of one of the pools in order to solve this equation. Here, we determined turnover of the dynamic water-exactable organic carbon (WEOC) pool (Hagedorn et al., 2004; Lechleitner et al., 2016) using time-series measurements as an approximation for the dynamics pool (. In this case, we can solve use the bulk radiocarbon signature at two time points to solve for (between 1 and 10.000 in 1 year steps) and (between 0 and 1 in 0.01 steps).



**Figure S1** Conceptual visualization illustrating visually (a) the grounds for the numerical approach and (b) the one and (c) two-pool model.

**SI1.1.3 Implications model choice on error propagation**

Intuitively, it makes sense that when one unknown is determined using two time-points, it is better constrained than when two unknowns are determined using two known values. Visually, we can see that if we use the 1-pool approach, a single minimum can be found by calculating the mean square error of the quadrate of both errors (Fig. 2, Eq. 8a and b).

### **S1.2 Comparison with other temporally resolved models**

From the scientific literature, we can discern two families of models dealing with temporally resolved datasets that all build on the equations laid out in Torn et al., (2009). Firstly, there is a group that matches the data to excel-based calculations without the help of optimization using atmospheric input data, e.g. in Schrumpf and Kaiser (2015). Our model differs slightly from this as it includes robust error reduction and a non-subjective estimate. Secondly, there is a group which uses the same equations and combine it with the strength of the Excel Solver function (www.solver.com) and error reduction (*Prior et al.*, 2007; *Baisden et al.*, 2013). We will assume that, as the concerned equations of radioactive decay are non-linear, that the non-linear function of the Excel solver function was used. In these cases, two pools are assumed to be present (one fast decadal pool and one slow millennial pool), there is a steady state and the time step is one year. The age of the passive pool is assumed to be constant (e.g. 1000 years) and the spin-up time starts early 19th century, forcing the model to choose a value of the fast pool which is <100 years. The numerical model presented in this study builds on these models by including a measured value of one of the pools instead of an estimated value.

**Table S1** Beatenberg Δ14C data and modelled turnover data, with single- and temporally- resolved radiocarbon data as visualized in Fig. 2.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Average depth (cm) | Δ14C 1997 | Δ14C 2014 | Turnover 1997  (y) | Turnover 2014  (y) | Turnover time-series (y) |
| Organic layerbulk | 210.91 | 98.95 | 28.7 | 79.7 | 14 |
| 2.5bulk | -17.61 | -17.15 | 404.6 | 412.8 | 410 |
| 2.5WEOC | 33.12 | 7.75 | 182 | 199.8 | 191 |



**Figure S2** Turnover time (y) for (a) no atmospheric lag and (b) a vegetation-dependent atmospheric lag (Table 2) in the soils of the study sites. Turnover times increase from decadal to centennial in the topsoil to millennial in the deep soil. The modeled vegetation-induced lag only affects the turnover times of the organic layer.



**Figure S3** Visualization of grain size distribution five sites at 10-20 cm depth in the mineral soil. The sites Alptal and Nationalpark are underlain by respectively shale and intercalating alluvial fan with silty and sandy layers.

## ***Table S2***Pedogenic oxides as determined by oxalate-exactable Fe and Al on soil samples on single profiles taken proximal to the plots (courtesy Stephan Zimmerman, WSL LWF).

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Othmarsingen | | | Lausanne | | | Alptal | | | Beatenberg | | | Nationalpark | | |
| Soil depth  (cm) | Fe (ppm) | Al (ppm) | Soil depth  (cm) | Fe (ppm) | Al (ppm) | Soil depth  (cm) | Fe (ppm) | Al (ppm) | Soil depth  (cm) | Fe (ppm) | Al (ppm) | Soil depth  (cm) | Fe (ppm) | Al (ppm) |
| 2.5 | 2273 | 1298 | 2.5 | 3356 | 1861 | 2.5 | 13160 | 2577 | 2 | 1072 | 748 | 2.5 | 3004 | 756 |
| 7.5 | 2423 | 1317 | 7.5 | 3400 | 1879 | 7.5 | 17145 | 2937 | 7 | 102 | 222 | 7.5 | 1709 | 273 |
| 15 | 2307 | 1222 | 15 | 3039 | 2030 | 15 | 16408 | 2731 | 15 | 133 | 280 | 15 | 1583 | 230 |
| 30 | 2348 | 1174 | 35 | 3100 | 1942 | 30 | 4958 | 1470 | 25 | 189 | 431 | 30 | 761 | 180 |
| 65 | 3868 | 1605 | 80 | 2095 | 1156 | 50 | 4564 | 1017 | 43 | 4178 | 1330 | 50 | 497 | 115 |
|  |  |  |  |  |  |  |  |  | 60 | 162 | 1914 | 76.5 | 568 | 139 |

**Table S3** Grain size distribution data of the five concerned sites.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Site | Depth | Grain size 0.1 | Grain size mean | Grain size 0.9 | Mode |
| Othmarsingen | 2.5 | 3.1 | 19.8 | 151.0 | 21.4 |
|  | 7.5 | 2.8 | 20.0 | 147.7 | 23.0 |
|  | 15 | 2.6 | 20.2 | 157.0 | 24.3 |
|  | 30 | 2.7 | 21.6 | 139.0 | 28.4 |
|  | 50 | 3.0 | 30.2 | 217.0 | 38.0 |
|  | 70 | 3.2 | 28.4 | 19.6 | 36.0 |
| Lausanne | 2.5 | 2.0 | 11.160 | 108.2 | 10.5 |
|  | 7.5 | 2.4 | 17.3 | 150.7 | 19.1 |
|  | 15 | 2.5 | 20.2 | 221.8 | 21.4 |
|  | 30 | 2.2 | 16.5 | 198.5 | 17.7 |
|  | 50 | 2.3 | 19.6 | 176.0 | 26.5 |
|  | 70 | 2.6 | 22.2 | 253.9 | 25.7 |
| Alptal | 2.5 | 2.4 | 9.9 | 26.8 | 12.2 |
|  | 7.5 | 2.5 | 12.3 | 36.6 | 16.9 |
|  | 15 | 2.0 | 9.7 | 34.8 | 13.4 |
|  | 30 | 1.9 | 8.3 | 27.0 | 10.6 |
| Beatenberg | 2.5 | 4.8 | 26.4 | 242.7 | 21.7 |
|  | 15 | 7.3 | 94.1 | 384.5 | 114.3 |
|  | 30 | 6.2 | 87.9 | 437.5 | 114.3 |
|  | 50 | 7.3 | 75.9 | 296.9 | 112.8 |
| Nationalpark | 2.5 | 3.0 | 17.8 | 107.2 | 15.3 |
|  | 7.5 | 1.7 | 9.5 | 87.7 | 8.9 |
|  | 15 | 2.0 | 11.9 | 84.3 | 10.7 |
|  | 30 | 3.0 | 22.8 | 706.1 | 623.6 |
|  | 50 | 2.7 | 19.0 | 454.5 | 11.2 |
|  | 70 | 3.4 | 36.9 | 857.7 | 690.0 |

**Table S4** Estimation potential contribution petrogenic carbon for two sites containing sedimentary carbon assuming for Alptal the signature of a sedimentary-carbon free soil and for Lausanne the shallower depth. The signature of the shale is assumed to be devoid of radiocarbon. The fossil contribution =

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Δ14C Alptal at 90 cm(‰) | Δ14C Beatenberg at 60 cm (‰) | Shale (‰) | Contribution fossil |
| Alptal Δ14C 90 cm ­­­(‰) | -640.3 | -421.3 | -1000 | 0.38 |
|  |  | Δ14C Lausanne at 80\_cm (‰) |  |  |
| Lausanne Δ14C 145 cm (‰) | -533.2 | -252.5 | -1000 | 0.38 |
| Lausanne Δ14C 210 cm (‰) | -403.5 | -252.5 | -1000 | 0.20 |
| Lausanne Δ14C 270 cm (‰) | -186.4 | -252.5 | -1000 | - |
| Lausanne Δ14C 310 cm (‰) | -820.2 | -252.5 | -1000 | 0.76 |

**Table S5** Modelled ages of bulk carbon, the dynamic pool, the slow pool and the relative size distribution.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Site | Depth | WEOC turnover (y) | Bulk turnover (y) | Modelled Fraction dynamic | Modelled Slow turnover (y) |
| Othmarsingen | 2.5 | 38.4 | 77 | 0.402 | 103 |
|  | 7.5 | 33.4 | 170 | 0.166 | 197 |
|  | 15 | 33.4 | 240 | 0.138 | 273 |
|  | 30 | 33.4 | 361 | 0.138 | 413 |
|  | 50 | 1001 | 1376 | - | - |
| Lausanne | 2.5 | 31.8 | 57 | 0.464 | 79 |
|  | 7.5 | 80 | 327 | 0.236 | 403 |
|  | 15 | 98.2 | 511 | 0.18 | 601 |
|  | 30 | 185.6 | 577 | - | - |
|  | 50 | 987.3 | 1816 | - | - |
|  | 70 | 1501.9 | 1633 | - | - |
| Alptal | 2.5 | 42.1 | 84 | - | - |
|  | 7.5 | 111.2 | 213 | - | - |
|  | 15 | 254.6 | 584 | - | - |
|  | 30 | 892.9 | 1366 | - | - |
| Beatenberg | 2.5 | 191.3 | 410 | 0.45 | 589 |
|  | 7.5 | 282.6 | 1175 | 0.176 | 1366 |
|  | 15 | 348.8 | 1656 | 0.18 | 1943 |
|  | 30 | 923.2 | 1917 | 0.464 | 2777 |
|  | 50 | 431.1 | 1297 | - | - |
| Nationalpark | 2.5 | 63.9 | 82 | 0.88 | 216 |
|  | 7.5 | 96.3 | 156 | 0.548 | 229 |
|  | 15 | 104.8 | 240 | 0.43 | 342 |
|  | 30 | 213.5 | 615 | 0.256 | 753 |