Modeling soil organic carbon dynamics in temperate forests with Yasso07

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**Supporting Material I: Supplementary tables and figures**

**Table S1 Information on forest inventories for stand biomass estimation**

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Site** | **Dominant Species** | | | **Soil** | **Forest inventory for stand biomass** | | | | **Storm event (yr)** | **No. of thinnings** |
| **Beginning(yr)** | **End (yr)** | **Span (yrs)** | **No. of inventories** |
| QR\_10 | *Quercus robur* | | | Calcisol | 1991 | 2009 | 18 | 7 |  | 1 |
| QR\_18 | *Quercus robur* | | | Planosol | 1991 | 2009 | 18 | 7 |  | 3 |
| QR\_40 | *Quercus robur* | | | Cambisol | 1992 | 2011 | 19 | 9 | 2009 | 2 |
| QR\_49 | *Quercus robur* | | | Planosol | 1991 | 2010 | 19 | 6 | 2009 | 3 |
| QR\_55 | *Quercus robur* | | | Calcisol | 1992 | 2009 | 17 | 6 |  | 2 |
| QR\_59 | *Quercus robur* | | | Luvisol | 1991 | 2010 | 19 | 8 |  | 2 |
| QR\_65 | *Quercus robur* | | | Cambisol | 1992 | 2012 | 20 | 6 |  | 3 |
| QR\_70 | *Quercus robur* | | | Luvisol | 1992 | 2011 | 19 | 7 |  | 3 |
| QR\_71 | *Quercus robur* | | | Luvisol | 1991 | 2009 | 18 | 6 |  | 2 |
| QP\_1 | *Quercus petraea* | | | Cambisol | 1991 | 2011 | 20 | 7 |  | 2 |
| QP\_3 | *Quercus petraea* | | | Cambisol | 1991 | 2009 | 18 | 7 |  | 3 |
| QP\_10 | *Quercus petraea* | | | Luvisol | 1991 | 2010 | 19 | 9 |  | 3 |
| QP\_18 | *Quercus petraea* | | | Luvisol | 1991 | 2009 | 18 | 7 |  | 3 |
| QP\_21 | *Quercus petraea* | | | Luvisol | 1991 | 2012 | 21 | 7 |  | 2 |
| QP\_27 | *Quercus petraea* | | | Luvisol | 1992 | 2009 | 17 | 9 | 1999 | 2 |
| QP\_35 | *Quercus petraea* | | | Luvisol | 1991 | 2011 | 20 | 6 |  | 2 |
| QP\_41 | *Quercus petraea* | | | Luvisol | 1991 | 2010 | 19 | 7 |  | 1 |
| QP\_51 | *Quercus petraea* | | | Cambisol | 1992 | 2004 | 12 | 5 | 1999 | 0 |
| QP\_57a | *Quercus petraea* | | | Planosol | 1992 | 2009 | 17 | 8 | 1999 | 1 |
| QP\_57b | *Quercus petraea* | | | Podzol | 1992 | 2009 | 17 | 5 |  | 2 |
| QP\_58 | *Quercus petraea* | | | Luvisol | 1991 | 2009 | 18 | 6 |  | 3 |
| QP\_60 | *Quercus petraea* | | | Planosol | 1992 | 2009 | 17 | 7 |  | 2 |
| QP\_61 | *Quercus petraea* | | | Luvisol | 1991 | 2009 | 18 | 7 | 1999 | 2 |
| QP\_68 | *Quercus petraea* | | | Calcisol | 1992 | 2009 | 17 | 7 | 1999 | 2 |
| QP\_72 | *Quercus petraea* | | | Luvisol | 1991 | 2009 | 18 | 8 |  | 3 |
| QP\_81 | *Quercus petraea* | | | Luvisol | 1992 | 2009 | 17 | 6 |  | 1 |
| QP\_86 | *Quercus petraea* | | | Luvisol | 1991 | 2009 | 18 | 6 | 1999 | 4 |
| QP\_88 | *Quercus petraea* | | | Cambisol | 1992 | 2011 | 19 | 8 |  | 3 |
| QP&QR\_67 | *Quercus petraea* & *Q. robur* | | | Cambisol | 1992 | 2004 | 12 | 5 | 1999 | 3 |
| QP&QR\_77 | *Quercus petraea* & *Q. robur* | | | Podzol | 1991 | 2009 | 18 | 6 | 1999 | 2 |
| PM\_23 | *Pseudotsuga menziesii* | | | Cambisol | 1991 | 2008 | 17 | 7 | 1999 | 1 |
| PM\_34 | *Pseudotsuga menziesii* | | | Cambisol | 1991 | 2010 | 19 | 7 |  | 4 |
| PM\_61 | *Pseudotsuga menziesii* | | | Luvisol | 1991 | 2011 | 20 | 7 |  | 3 |
| PM\_65 | *Pseudotsuga menziesii* | | | Cambisol | 1992 | 2004 | 12 | 5 |  | 0 |
| PM\_69 | *Pseudotsuga menziesii* | | | Cambisol | 1991 | 2004 | 13 | 7 | 1999 | 1 |
| PM\_71 | *Pseudotsuga menziesii* | | | Podzol | 1993 | 2013 | 20 | 11 |  | 5 |
| PA\_8 | *Picea abies* | | | Podzol | 1992 | 2009 | 17 | 5 |  | 1 |
| PA\_34 | *Picea abies* | | | Podzol | 1991 | 2009 | 18 | 7 | 2009 | 3 |
| PA\_39a | *Picea abies* | | | Luvisol | 1991 | 2004 | 13 | 5 |  | 1 |
| PA\_63 | *Picea abies* | | | Andosol | 1991 | 2009 | 18 | 7 |  | 3 |
| PA\_71 | *Picea abies* | | | Podzol | 1991 | 2004 | 13 | 5 |  | 1 |
| PA\_73 | *Picea abies* | | | Cambisol | 1992 | 2007 | 15 | 5 |  | 2 |
| PA\_74 | *Picea abies* | | | Luvisol | 1991 | 2009 | 18 | 8 |  | 3 |
| PA\_81 | *Picea abies* | | | Podzol | 1992 | 2004 | 12 | 5 |  | 1 |
| PA\_87 | *Picea abies* | | | Podzol | 1991 | 2009 | 18 | 7 | 1999 | 2 |
| PA\_88 | *Picea abies* | | | Cambisol | 1992 | 1999 | 7 | 3 | 1999 | 0 |
| FS\_2 | *Fagus sylvatica* | | | Luvisol | 1992 | 2009 | 17 | 6 |  | 2 |
| FS\_3 | *Fagus sylvatica* | | | Cambisol | 1991 | 2009 | 18 | 8 |  | 3 |
| FS\_4 | *Fagus sylvatica* | | | Cambisol | 1992 | 2009 | 17 | 5 |  | 0 |
| FS\_9 | *Fagus sylvatica* | | Podzol | | 1992 | 2009 | 17 | 6 |  | 1 |
| FS\_14 | *Fagus sylvatica* | | Cambisol | | 1991 | 2013 | 22 | 8 |  | 3 |
| FS\_21 | *Fagus sylvatica* | | Leptosol | | 1991 | 2009 | 18 | 6 | 1999 | 1 |
| FS\_25 | *Fagus sylvatica* | | Cambisol | | 1991 | 2009 | 18 | 7 |  | 3 |
| FS\_26 | *Fagus sylvatica* | | Leptosol | | 1991 | 2009 | 18 | 6 |  | 1 |
| FS\_29 | *Fagus sylvatica* | | Luvisol | | 1991 | 2009 | 18 | 6 |  | 3 |
| FS\_30 | *Fagus sylvatica* | | Podzol | | 1991 | 2012 | 21 | 7 |  | 2 |
| FS\_52 | *Fagus sylvatica* | | Leptosol | | 1991 | 2005 | 14 | 6 | 1999 | 2 |
| FS\_54a | *Fagus sylvatica* | | Planosol | | 1992 | 1999 | 7 | 3 | 1999 | 1 |
| FS\_54b | *Fagus sylvatica* | | Leptosol | | 1992 | 1999 | 7 | 4 | 1999 | 0 |
| FS\_55 | *Fagus sylvatica* | | Podzol | | 1992 | 2011 | 19 | 8 | 1999 | 2 |
| FS\_60 | *Fagus sylvatica* | | Luvisol | | 1992 | 2009 | 17 | 7 | 1999 | 1 |
| FS\_64 | *Fagus sylvatica* | | Cambisol | | 1992 | 2011 | 19 | 8 |  | 3 |
| FS\_65 | *Fagus sylvatica* | | Cambisol | | 1992 | 2009 | 17 | 7 |  | 2 |
| FS\_76 | *Fagus sylvatica* | | Luvisol | | 1991 | 2009 | 18 | 9 |  | 2 |
| FS\_81 | *Fagus sylvatica* | | Podzol | | 1992 | 2009 | 17 | 6 |  | 1 |
| FS\_88 | *Fagus sylvatica* | | Cambisol | | 1992 | 2009 | 17 | 8 |  | 2 |
| LD\_5 | *Larix deciduas* | | Regosol | | 1991 | 2014 | 23 | 6 |  | 2 |
| PN\_20 | *Pinus nigra* | | Cambisol | | 1991 | 2009 | 18 | 7 |  | 2 |
| PN\_41 | *Pinus nigra* | | Podzol | | 1991 | 2004 | 13 | 6 | 1999 | 2 |
| PP\_17 | *Pinus pinaster* | | Arenosol | | 1991 | 2009 | 18 | 7 | 1999 | 1 |
| PP\_20 | *Pinus pinaster* | | Cambisol | | 1991 | 2004 | 13 | 5 |  | 2 |
| PP\_40a | *Pinus pinaster* | | Podzol | | 1992 | 2004 | 12 | 8 |  | 2 |
| PP\_40b | *Pinus pinaster* | | Podzol | | 1992 | 2009 | 17 | 7 | 2009 | 2 |
| PP\_40c | *Pinus pinaster* | | Podzol | | 1992 | 2009 | 17 | 8 | 2009 | 3 |
| PP\_72 | *Pinus pinaster* | | Podzol | | 1991 | 2010 | 19 | 7 |  | 4 |
| PP\_85 | *Pinus pinaster* | | Arenosol | | 1991 | 2011 | 20 | 6 |  | 3 |
| PS\_4 | *Pinus sylvestris* | | Leptosol | | 1991 | 2004 | 13 | 4 |  | 0 |
| PS\_15 | *Pinus sylvestris* | | Cambisol | | 1991 | 2011 | 20 | 7 | 1999 | 2 |
| PS\_35 | *Pinus sylvestris* | | Luvisol | | 1991 | 2013 | 22 | 7 |  | 3 |
| PS\_41 | *Pinus sylvestris* | Podzol | | | 1991 | 2004 | 13 | 6 | 1999 | 2 |
| PS\_44 | *Pinus sylvestris* | Luvisol | | | 1991 | 2010 | 19 | 7 |  | 3 |
| PS\_45 | *Pinus sylvestris* | Planosol | | | 1991 | 2005 | 14 | 7 |  | 2 |
| PS\_61 | *Pinus sylvestris* | Luvisol | | | 1991 | 1999 | 8 | 3 | 1999 | 0 |
| PS\_63 | *Pinus sylvestris* | Cambisol | | | 1991 | 2009 | 18 | 7 | 1999 | 0 |
| PS\_67a | *Pinus sylvestris* | Podzol | | | 1992 | 2009 | 17 | 7 | 1999 | 1 |
| PS\_67b | *Pinus sylvestris* | Podzol | | | 1992 | 2013 | 21 | 9 | 1999 | 3 |
| PS\_76 | *Pinus sylvestris* | Podzol | | | 1991 | 2009 | 18 | 7 | 1999 | 1 |
| PS\_78 | *Pinus sylvestris* | Podzol | | | 1992 | 2007 | 15 | 6 | 1999 | 1 |
| PS\_88 | *Pinus sylvestris* | Podzol | | | 1992 | 2007 | 15 | 6 | 1999 | 1 |
| PS\_89 | *Pinus sylvestris* | Podzol | | | 1991 | 1999 | 8 | 4 | 1999 | 1 |
| AA\_5 | *Abies alba* | Cambisol | | | 1991 | 2009 | 18 | 5 |  | 1 |
| AA\_7 | *Abies alba* | Podzol | | | 1991 | 2010 | 19 | 6 |  | 1 |
| AA\_9 | *Abies alba* | Podzol | | | 1992 | 2008 | 16 | 7 | 2009 | 2 |
| AA\_11 | *Abies alba* | Luvisol | | | 1992 | 2009 | 17 | 8 |  | 2 |
| AA\_25 | *Abies alba* | Cambisol | | | 1991 | 2012 | 21 | 8 |  | 3 |
| AA\_26 | *Abies alba* | Cambisol | | | 1991 | 2014 | 23 | 6 |  | 2 |
| AA\_38 | *Abies alba* | Cambisol | | | 1992 | 2009 | 17 | 6 |  | 1 |
| AA\_39 | *Abies alba* | Cambisol | | | 1991 | 2009 | 18 | 6 |  | 2 |
| AA\_57 | *Abies alba* | Cambisol | | | 1992 | 2009 | 17 | 9 | 1999 | 2 |
| AA\_63 | *Abies alba* | Cambisol | | | 1992 | 2004 | 12 | 6 |  | 1 |
| AA\_68 | *Abies alba* | Cambisol | | | 1992 | 2012 | 20 | 7 |  | 3 |
|  |  | | | |  |  |  |  |  |  |
|  |  | | | | **Beginning (yr)** | **End (yr)** | **Mean span  (yrs)** | **Mean no. of inventories** | **Frequency (storms/100 yrs)** | **Frequency (thinnings/10 yrs)** |
|  | All sites: | | | | 1991 | 2014 | 17.0 | 6.6 | 2.1 | 1.1 |
|  |  | | | |  |  |  |  |  |  |

**Table S2 Linear regressions explaining the variability in annual carbon change residuals according to soil physical and chemical properties**

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Variable** | **Broadleaves** | | | |  | **Conifers** | | | |
| **R²** | **Slope** | **Intercept** | ***P*-value** |  | **R²** | **Slope** | **Intercept** | ***P*-value** |
| Total nitrogen (in tN/ha) | 0.257 | -0.217 | 1.006 | <0.001\*\*\* |  | 0.191 | -0.198 | 0.056 | <0.01\*\* |
| Proportion of sand (in %) | 0.152 | 0.010 | -0.221 | <0.01\*\* |  | 0.008 | 0.003 | -0.944 | >0.05 |
| Exchangeable Mg (in kmol/ha) | 0.138 | -0.011 | 0.255 | <0.01\*\* |  | 0.000 | 0.000 | -0.761 | >0.05 |
| Exchangeable K (in kmol/ha) | 0.109 | -0.071 | 0.374 | <0.05\* |  | 0.001 | 0.020 | -0.807 | >0.05 |
| Proportion of clay (in %) | 0.099 | -0.016 | 0.435 | <0.05\* |  | 0.016 | -0.013 | -0.561 | >0.05 |
| Proportion of silt (in %) | 0.094 | -0.010 | 0.566 | <0.05\* |  | 0.004 | -0.003 | -0.660 | >0.05 |
| Exchangeable Al (in kmol/ha) | 0.070 | -0.004 | 0.360 | >0.05 |  | 0.002 | -0.001 | -0.704 | >0.05 |
| Total phosphorus (in tN/ha) | 0.045 | -0.011 | 0.304 | >0.05 |  | 0.000 | 0.000 | -0.770 | >0.05 |
| Exchangeable Ca (in kmol/ha) | 0.016 | 0.000 | 0.135 | >0.05 |  | 0.004 | 0.000 | -0.729 | >0.05 |
| pH | 0.005 | 0.042 | -0.099 | >0.05 |  | 0.000 | 0.018 | -0.839 | >0.05 |
| Carbon:nitrogen ratio | 0.000 | 0.001 | 0.069 | >0.05 |  | 0.019 | 0.009 | -1.063 | >0.05 |

Note: the grey zone indicates the variables chosen for plotting in Figure 5 in the manuscript. R² = coefficient of determination.

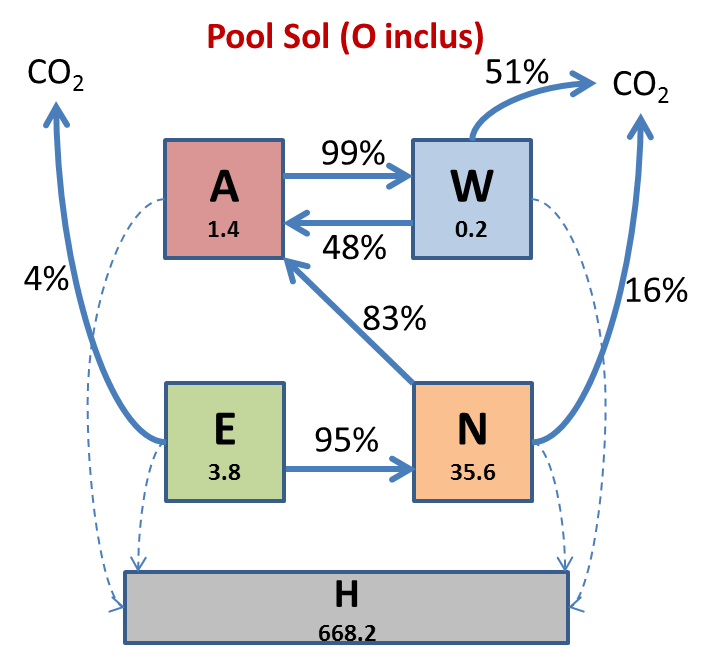


Figure S1 Partitioning of soil carbon pools in Yasso07 (after Tuomi et al., (2011b)). Letters: A: hydrolysable in Acid; W: soluble in Water; E: soluble in Ethanol; N: Non-soluble; H: recalcitrant Humus. Solid arrows represented the carbon flows that are statistically significant from zero. Dashed arrows refer to the carbon flows toward H. Values in each pool are examples of inverse mean residence time (*1/k*, in years) estimated with Yasso07 parameters.

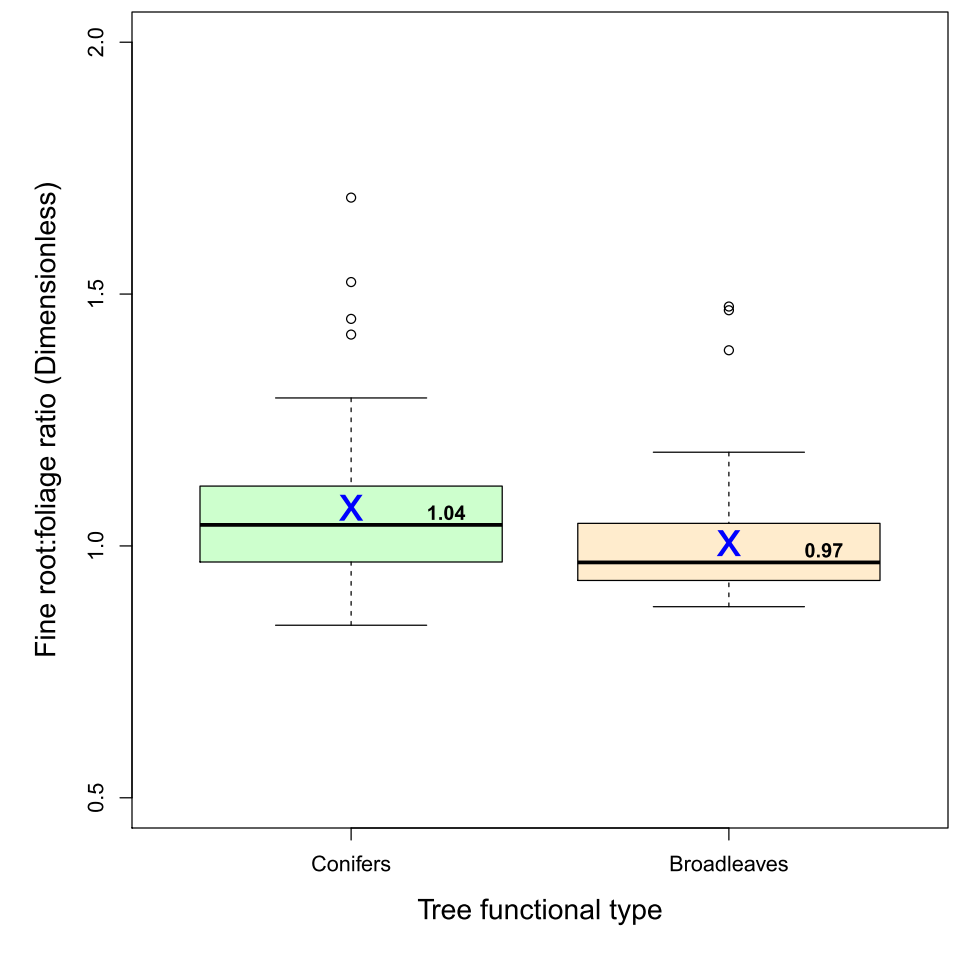


Figure S2: Distributions of ﬁne-root-to-foliage ratio of litter input in different tree functional types calculated with the equation from Raich and Nadelhoffer (1989), see Jonard et al., (2017). For each boxplot, the low and top edges of the box correspond respectively to the 25th and 75th percentile data points; the line within the box represents the median; and hollow points indicate outliers. Median values are shown beside median lines. “X” indicates mean values: 1.08 ± 0.02 (mean ± standard error) for sites dominated by conifers and 1.01 ± 0.02 for sites dominated by broadleaves.

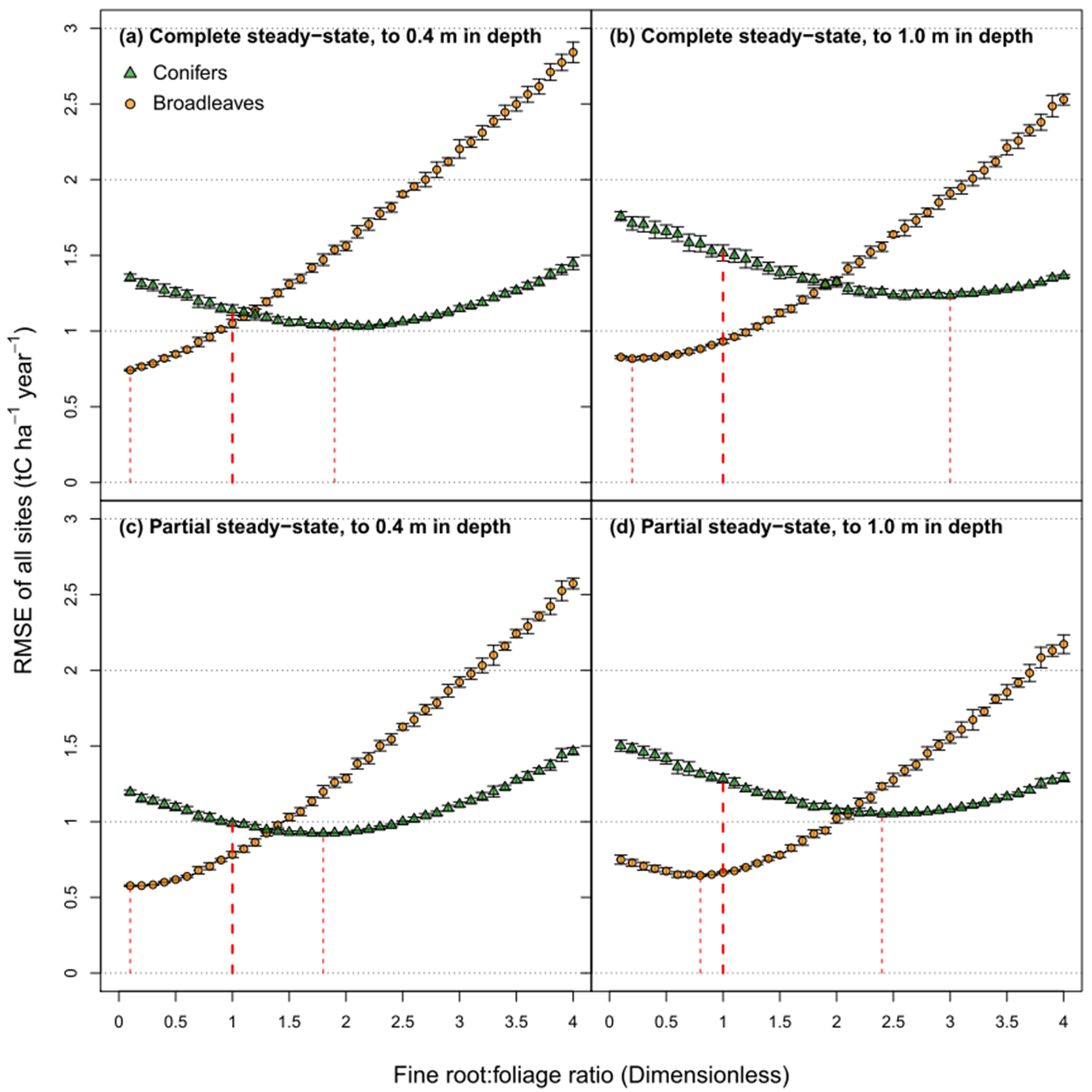


Figure S3: Influence of the choice of model initialization method for soil carbon quantity (stocks to 0.4 m in depth versus stocks to 1.0 m in depth) and quality (complete versus partial steady-state assumption) and the choice of ﬁne-root-to-foliage ratio for litter input (from 0.1 to 4.0) on Yasso07 performance for the French RENECOFOR data. RMSE – root mean square error; Error bars are standard deviations of 10 simulations with different, randomly chosen parameters. Red dashed lines perpendicular to the *x*-axis: the two thin lines show the values of ﬁne-root-to-foliage ratio for the minimum RMSE for broadleaves and conifers, respectively; the thick red dashed line is at 1.0 (the ratio used for the results presented). The case in (c) gives the best model fit (lowest RMSE), but the case in (d) was preferentially chosen, since Yasso07 is validated by and predicts soil carbon data to a depth of 1.0 m.

Z:\MAO_xuexi\Article\Yosso07\data\201506_EffectOfInitalCStockOnCarbonDynamique\20161126_plotFig11_sensitivity_goCS_legend.tif

Figure S4: Sensitivity analysis of the impact of the carbon pool composition of the initial soil C stock (*x*-axis (↙), in %) and simulated duration (*y*-axis (→), in logarithmic years) on the final soil carbon stock (*z*-axis (↑), in tC ha-1). Here, the results were generated with the mean broadleaved litter input quantity and quality of the RENECOFOR sites. Initial soil carbon stock was fixed to 100 tC ha-1. Subplots in each row show the final change in stocks for one type of soil carbon pool (i.e. A, W, E, N or H). In the 2nd row, W and E were combined due to their low quantities in most cases. Subplots in each column show the effect of one type of soil chemical group on the final stocks of the five soil carbon pools (the first four individually, plus total stock). In each subplot, a membrane (with grids for a three-dimensional effect) represents the loess fit (polynomial equation) to *z* (in tC ha-1) as a function of *x* and *y*; the color of the membrane represents the relative value of *z* (in %), i.e. the proportion of one soil carbon pool within the total soil carbon stock. No color is assigned to the membranes in the last row, because the relative value is 100 %. Blue lollipops denote the standard deviations of the simulated mean *z* (on the membrane surface) given each (*x*, *y*) location, which follow a systematic distribution.

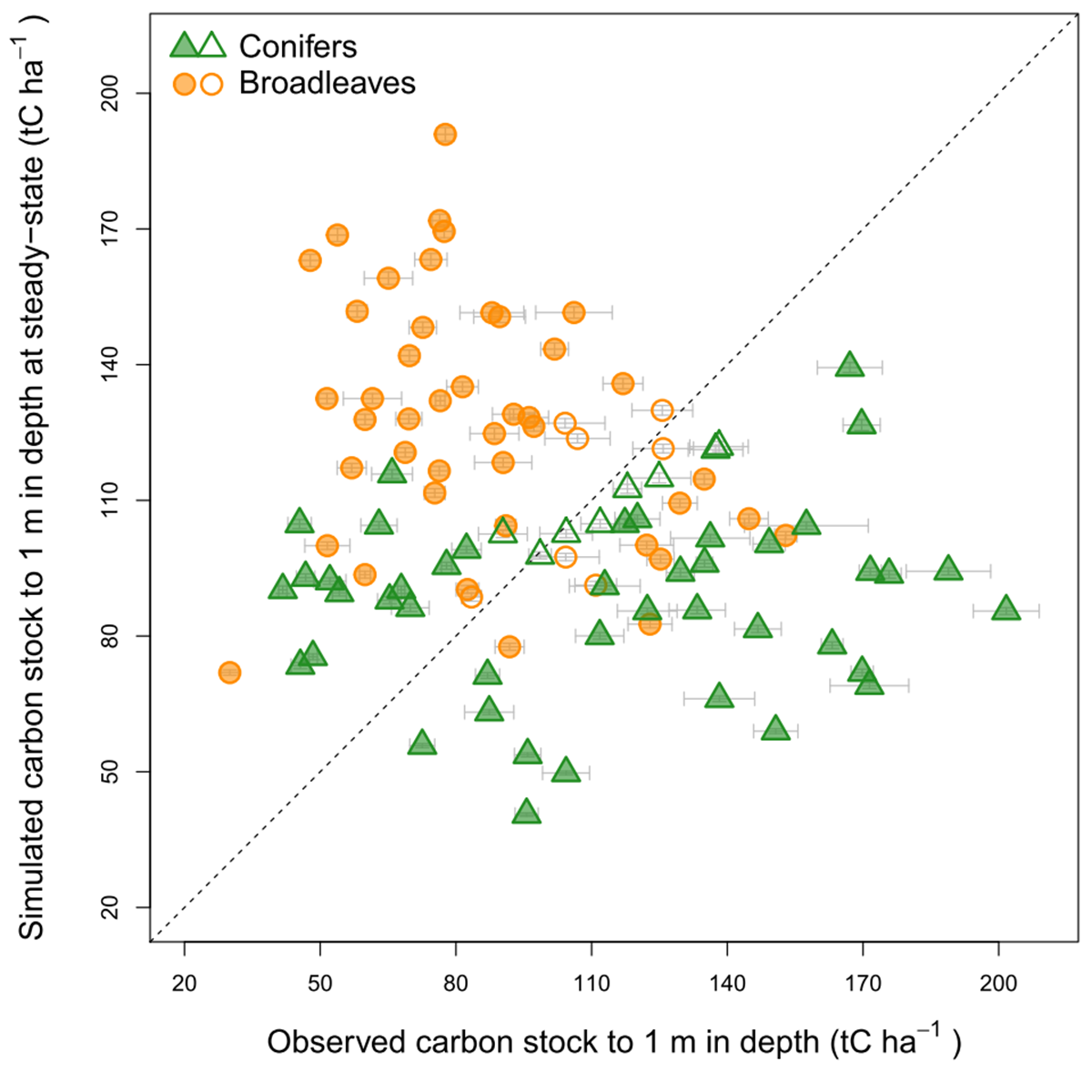


Figure S5: Comparison between the steady-state carbon stock to 1.0 m in depth (CS, in tC ha-1) and the observed carbon stock to 1.0 m at *t1*, used for model input. Circles and triangles represent sites dominated by broadleaves and conifers, respectively. The chosen ﬁne-root-to-foliage ratio for broadleaves and conifers is 1.0. Error bars represent standard errors; hollow and filled points respectively represent non-significant and significant differences between simulated and observed ACC according to t-test (at a 95% confidence interval).

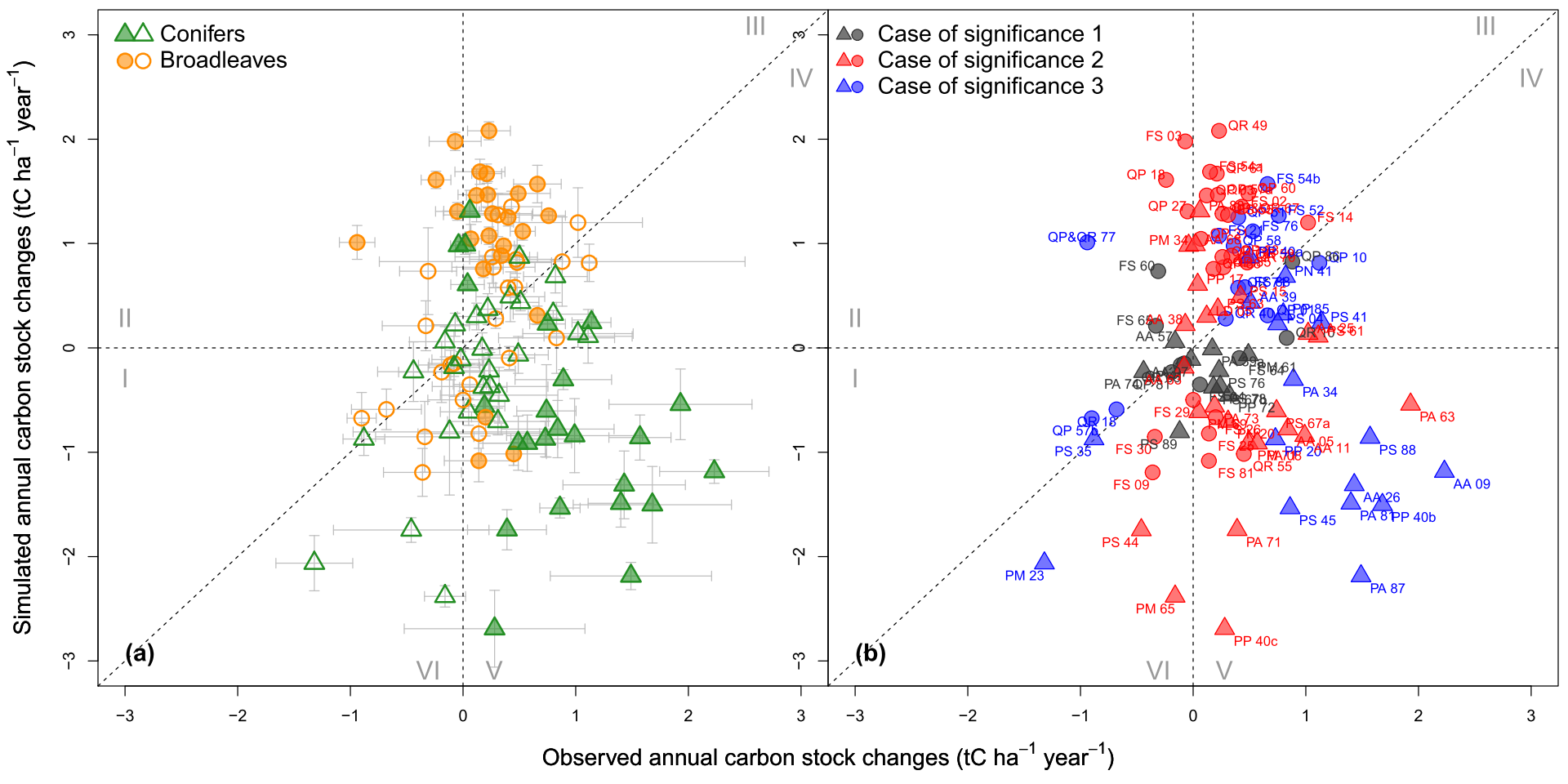


Figure S6: Comparison between simulated and observed annual changes in carbon stocks (ACC, in tC ha-1 year-1). Circles and triangles represent sites dominated by broadleaves and conifers, respectively. The complete steady-state assumption was used to initialize carbon quality of the stock to 1.0 m in depth. The chosen ﬁne-root-to-foliage ratio for broadleaves and conifers is 1.0. To facilitate readability, Roman numerals (I-VI) denote the six zones in which data points are distributed. In (a), error bars represent standard errors; hollow and filled points respectively represent non-significant and significant differences between simulated and observed ACCs according to t-test (at a 95% confidence interval). In (b), case of significance: 1 – no significant difference from 0 for either observed or simulated ACC; 2 - a significant difference from 0 for either observed or simulated ACC, and 3 - a significant difference from 0 for both observed and simulated ACC.

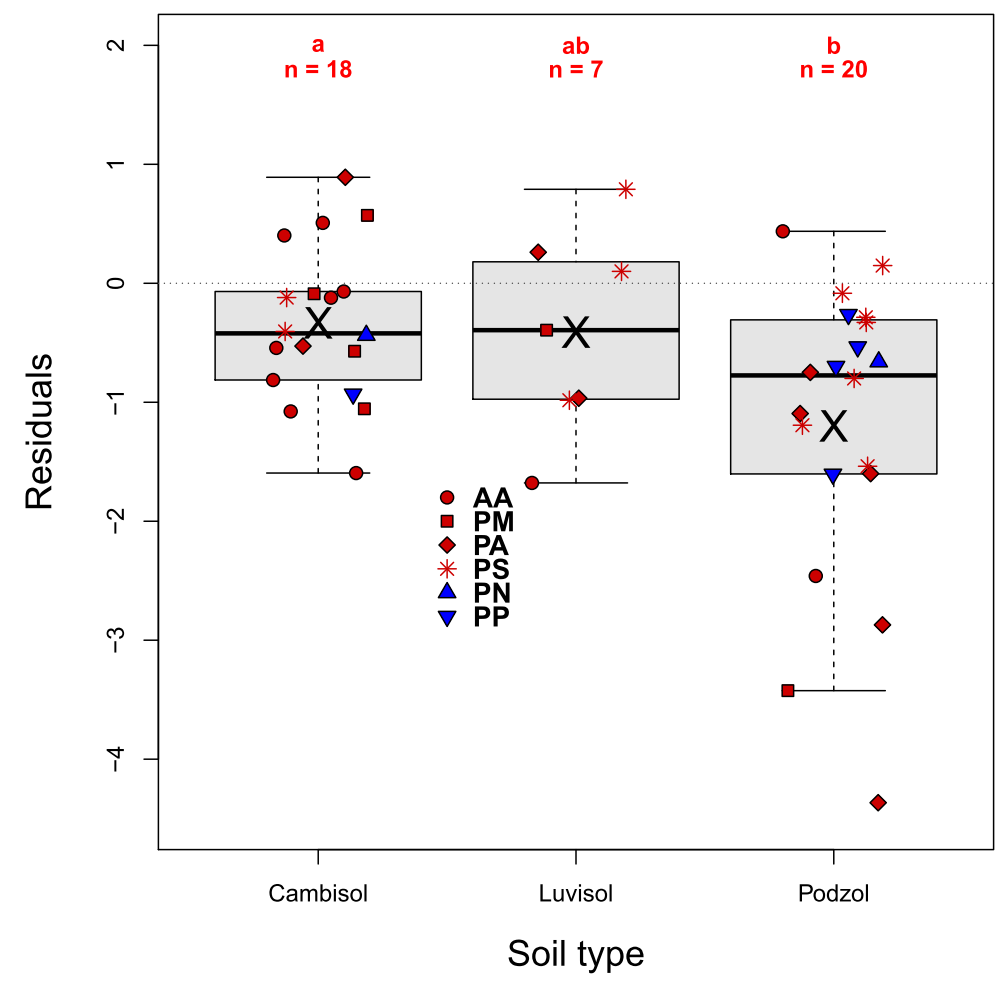


Figure S7 Distribution of the residuals (simulated changes minus observed changes in annual carbon stocks) of Yasso07’s fit for sites dominated by conifers. For each boxplot, the lower and top edge of the box respectively correspond to the 25th and 75th percentile data points; the line inside the box represents the median; there are no outlier points in this case. “X” indicates mean values: -0.33 ± 0.15 (mean ± standard error) for cambisol,-0.41 ± 0.32 for luvisol and -1.20 ± 0.28 for podzol. Species acronyms: AA – *Abies alba*; PM – *Pseudotzuga menziesii*; PA – *Picea abies*; PS – *Pinus sylvestris*; PN – *Pinus nigra*; PP – *Pinus pinaster*. Letters above the boxplots indicate diagnostics according to the Tukey HSD test. Colors for different species: deep red for species that can be found on all the three types of soil; blue for species that can only be found on cambisols and podzols, but not on luvisols.

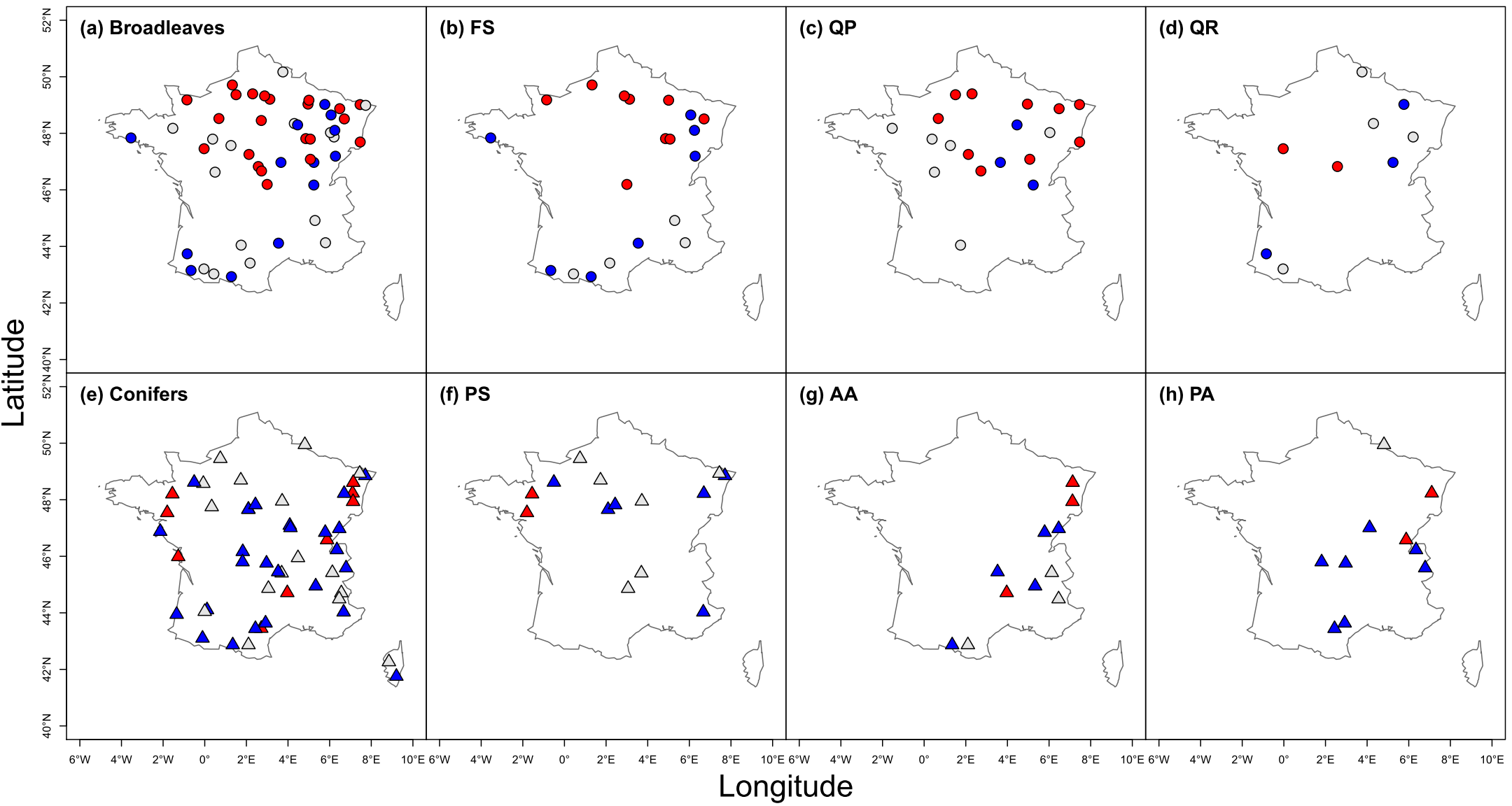


Figure S8: Spatial visualization of residuals (i.e. the difference between simulated and observed changes in annual carbon) for sites dominated by broadleaves (a) and conifers (b). Colors: red – overestimation with residuals being significantly > 0; blue – underestimation with residuals being significantly < 0; grey – residuals that are not significantly different from 0. Species abbreviations: FS – *Fagus sylvatica*; QP– *Quercus petraea*; QR - *Quercus robur* (*including* two mixed *Quercus* sites); PS - *Pinus sylvestris*; AA- *Abies alba*; PA - *Picea abies*.

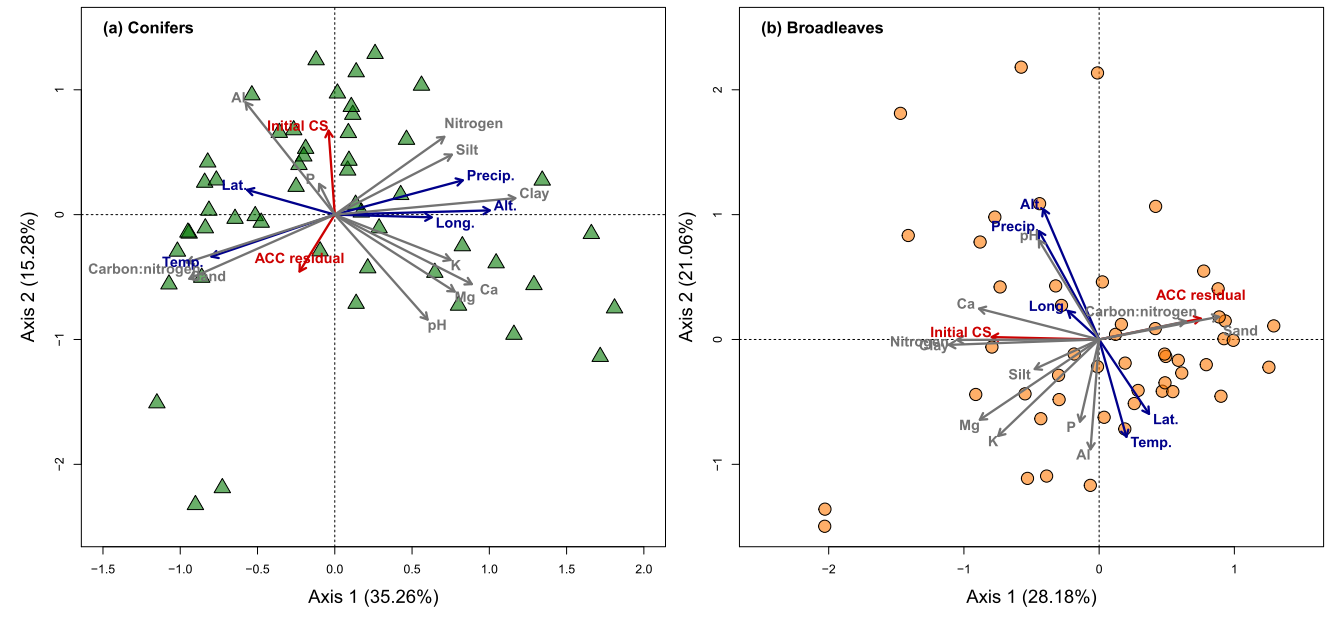


Figure S9 Relationships among indicators of site features and model predictions with principal component analyses for sites dominated by conifers (a) and broadleaves (b), respectively. Colors of arrows: red – residuals of annual carbon change and observed initial carbon stock; grey – soil physical and chemical properties; blue –site geographical and climatic variables. Each point corresponds to one RENECOFOR site. See Table S2 for the full list of soil properties.