Forest manipulation experiment reveals divergent controls on the sources and age of lateral DOC and CO_2 export

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Table of contents

1 Introduction

1.1 General Context

- Lateral C export is a significant fraction of watershed C balance.
- Forested catchments contain a large OM storage that could sustain DOC export for decades (Ledesma et al. 2013)
- LCE and NEE are connected over long timescale, by hydrology (Öquist et al. 2014)
- Isotopic values of C (stable and radiogenic) can inform us on the sources and age of C.

1.2 Research Question

- What are the controls over the sources and age of lateral CO2 and DOC export in forested catchments?
- Can a forest manipulation experiment (forest clearcut and ditch cleaning) provide new insight to test ongoing hypothesis on the controls of LCE in forested catchments?

1.3 Hypothesis

- The CO2 source and age is more closely linked to the forest C sink (A. Campeau et al. 2019), so clearcutting the forest should have an impact on C sources and age
- The DOC source and age is linked to discharge (Audrey Campeau et al. 2017) or water table position (A. Campeau et al. 2019), so changes in watershed hydrology, caused by clear-cutting and draining, should change the source and age of DOC.

1.4 Main Conclusion

DOC is controled more by *hydrological processes*, which determines what material is being mobilised, while CO2 is controled more by *biological processes,* which fuels CO2 in the watershed. Both are therefore controled by different processes, but will likely respond to changes in climate, albeit via different drivers.

2 Methodology

2.1 Study Site and Treatment:

- Six headwater catchments are included in this study:
  - 2 pristine sites (C1 and C2)
  - 4 treated watersheds (DC1 to DC4).
- The DC sites received different treatments:
  - Forest in all four sites was clearcut - around July 2020.
  - Two sites, DC1 and DC3, were also ditch cleaned - in September 2021.
  - The treatments are named as follow (pristine, clear-cut and ditch cleaning)

2.2 Map of the study sites (draw schematic instead)

2.3 Field measurements:

- All four sites are monitored for flow and water chemistry on a near continuous basis.
- Radiocarbon and stable C isotope measurements were collected at those six sites simultaniously and throughout various treatment stages.
- 14C measurements
  - Start 2020-03-12
  - End 2022-10-25

3 Results

3.1 Hydrographs and carbon concentrations

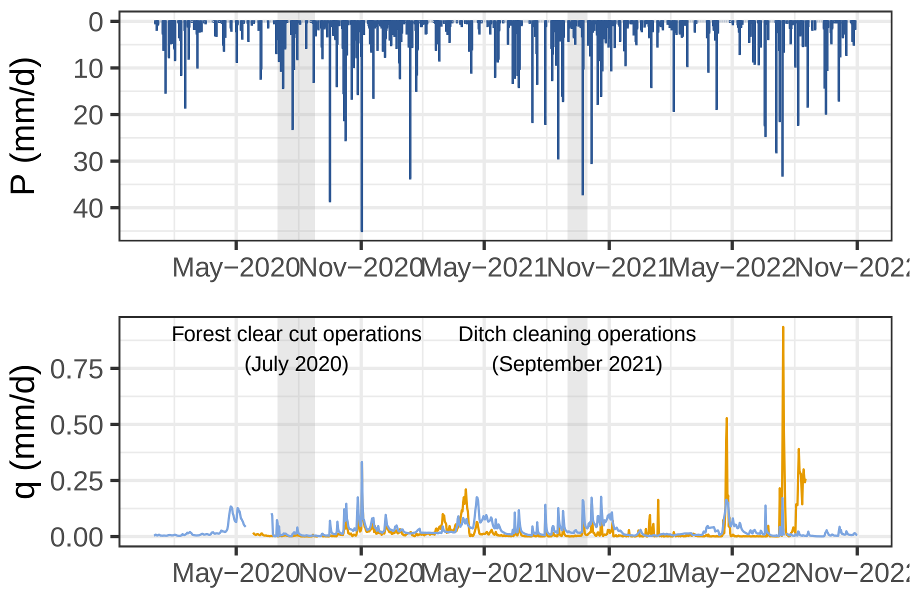

Figure 1: Precipitation and discharge timeseries

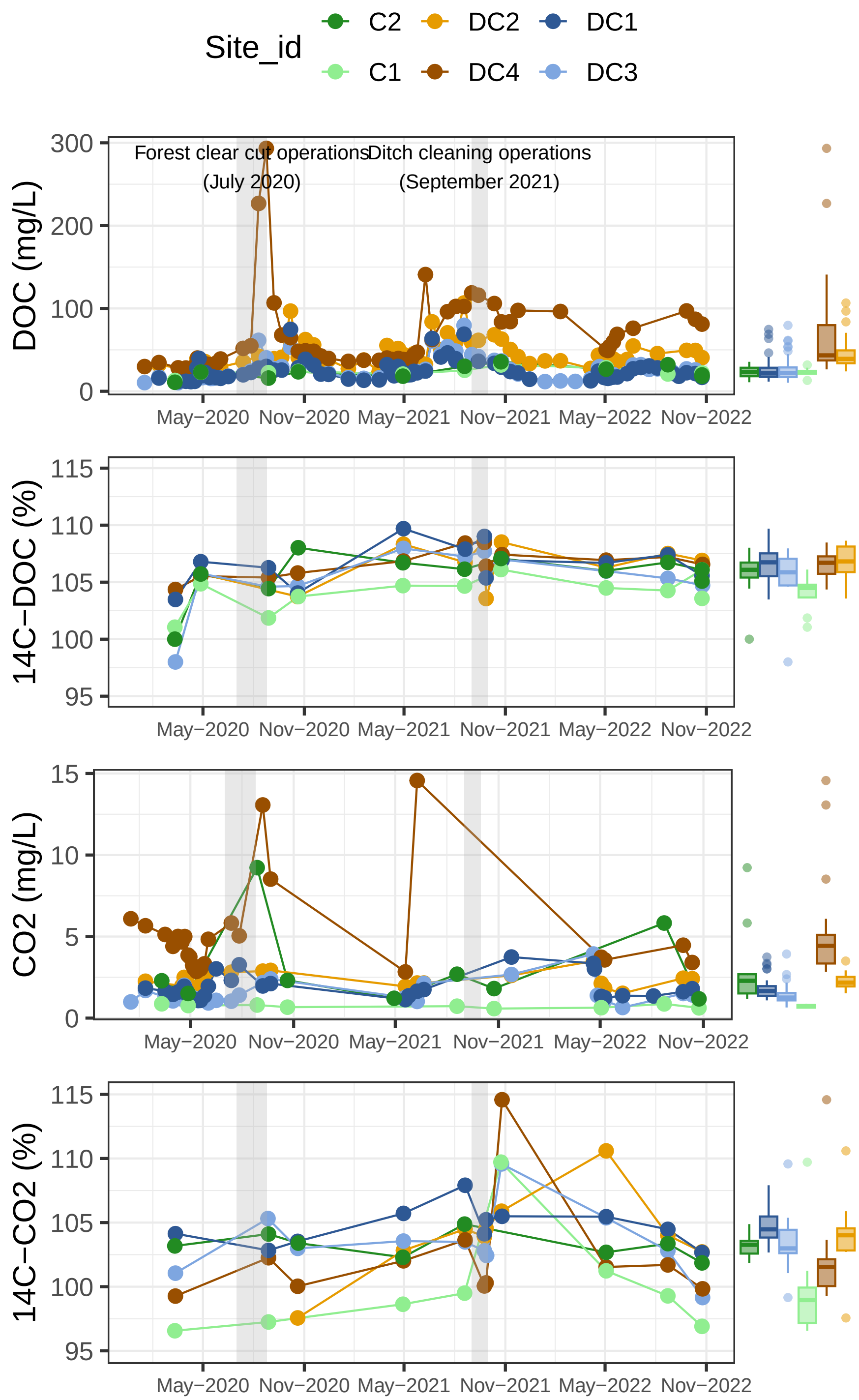

Figure 2: C concentration and radiocarbon content timeseries coloured by sites

3.1.0.1 Dunn's test | ^{1} C and [C] ~ Site

```
# A tibble: 6 x 5
  Site  `[DOC]` `14C-DOC` `[CO2]` `14C-CO2`
  <fct>   <dbl>     <dbl>   <dbl>     <dbl>
1 C2       23.2      106.    2.29      103.
2 C1       22.5      104.    0.73       99.0
3 DC2      39.1      107.    2.17      104.
4 DC4      44.1      107.    4.43      102.
5 DC1      21.4      107.    1.66      104.
6 DC3      22.0      106.    1.26      103.
```

```
  Site [DOC] 14C-DOC [CO2] 14C-CO2
1   C2     a      ab   abc     abc
2   C1     a       a     d       a
3  DC2     b       b     a      bc
4  DC4     b       b     b      ab
5  DC1     a       b    ac       c
6  DC3     a      ab    cd     abc
```

Interpretation

Trend:

- No obvious trends over time in C concentration or 14C content
- There was a clear peak in DOC and CO2 concentration at DC4 during clearcut opperations.

Differences between sites:

- CO2 and DOC concentration at DC4 is consistently higher than the other sites, followed with DC2, and DC1 and DC3.
- 14C-DOC is not different across sites
- 14C-CO2 is significantly lower at DC4, followed with DC3 and DC2, DC1 which is significantly higher

Q data

The database contains DC3 and DC2 flow data, one ditch cleaned while the other only clearcut. Other timeseries are incomplete.

3.2 Differences across treatments

Is there a significant change in the median ^{14}C content of CO_2 and DOC between sites or treatment, based on their distribution ?

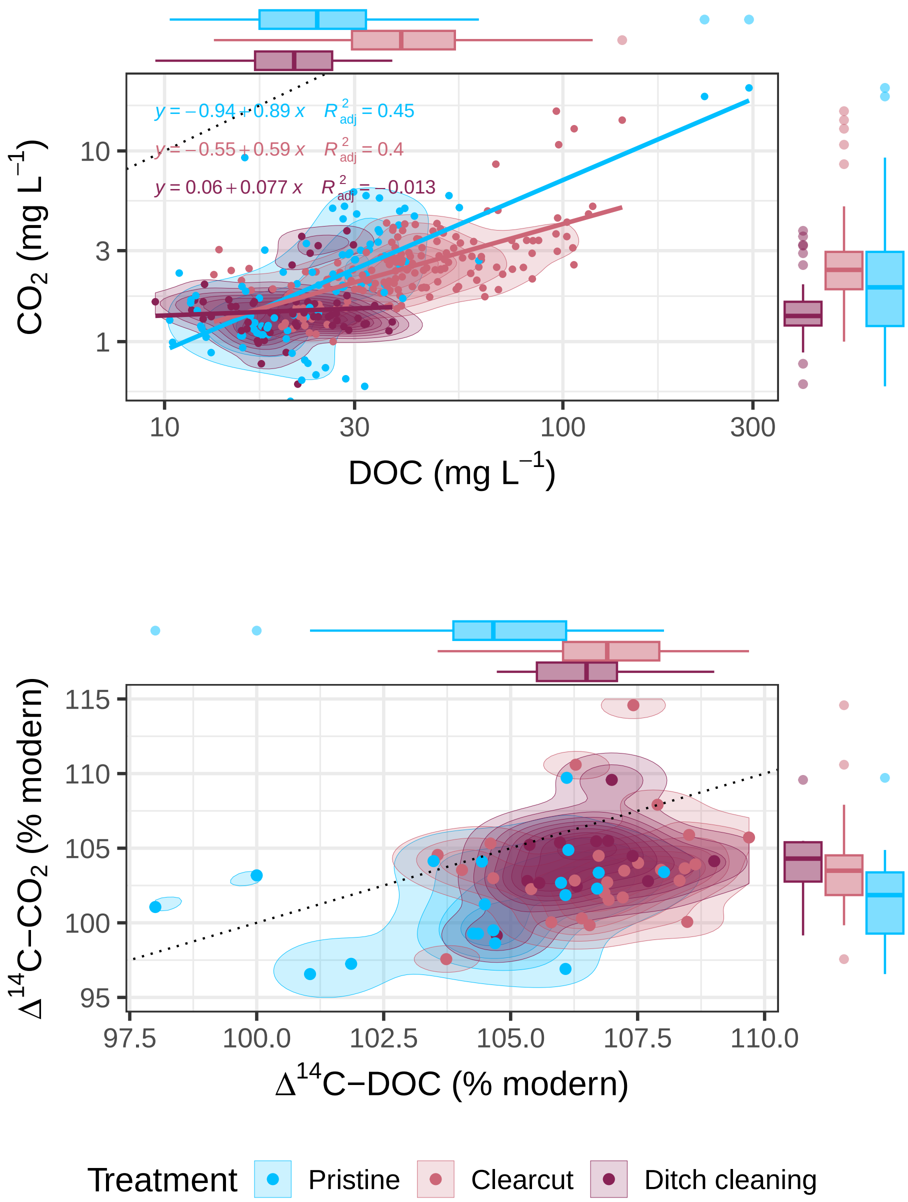

Figure 3: relationship between C concentration and radiocarbon content of CO2 and DOC coloured by treatment

ANOVA

```
ANOVA Table (type II tests)
```

```
                     Effect DFn DFd       F        p p<.05   ges
1           CO2_mgL_filled   1 317 459.060 1.36e-63     * 0.592
2                Treatment   2 317  29.092 2.51e-12     * 0.155
3 CO2_mgL_filled:Treatment   2 317   9.272 1.22e-04     * 0.055
```

3.2.0.1 Dunn's test | ^{1} C et [C]~ Treatment

```
            Site 14C-DOC [DOC] 14C-CO2 [CO2]
1       Pristine       a     a       a     a
2       Clearcut       b     b      ab     a
3 Ditch cleaning       b     a       b     a
```

> **Interpretation**
>
> **Treatment effect on C concentrations:**
>
> - The DOC concentrations are significantly higher following clearcut treatment compared with ditchcleaned and pristine conditions (short term effect of ditch cleaning can compensate?)
> - The CO2 concentration do not differ significantly across treatment
> - The relationship between CO2 and DOC concentration is positive for pristine condition, but slope becomes less significant with clearcut and not significant (slope =0) with ditch cleaning. Hence the DOC concentration continues to vary across a wide range but the CO2 becomes more stable.
>
> **Treatment effect on 14 content**
>
> - The ^{14}C-DOC is significantly lower in the pristine (group a) compared with clearcut and ditch cleaning sites.
> - The ^{14}C-CO_2 is doesn't differ significantly across treatments

3.3 Relationships - controls on C sources, age and concentrations

3.3.1 Hydrological control over C concentrations

Is the radiocarbon age or concentration of DOC and CO_2 controled by runoff, and does this relationship changes after treatment?

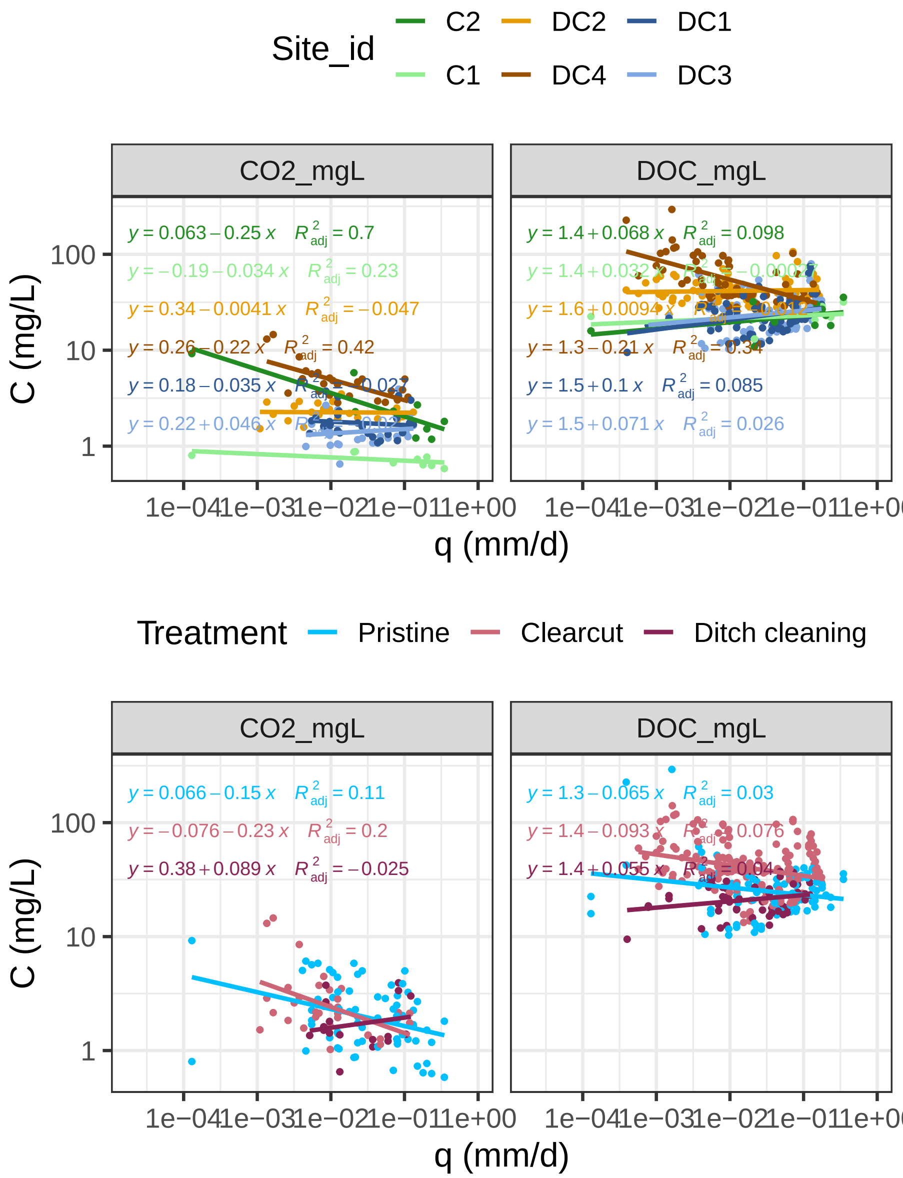

Figure 4: relationship between C concetration and discharge coloured by site and treatment

3.3.1.1 ANCOVA test

Is there a significant difference in the hydrological response of **DOC** concentrations between *Treatments or Sites*?

```
ANOVA Table (type II tests)

               Effect DFn DFd      F        p p<.05   ges
1          q_md_filled   1 307  3.090 8.00e-02       0.010
2            Treatment   2 307 20.164 5.92e-09     * 0.116
3 q_md_filled:Treatment   2 307  0.389 6.78e-01       0.003
```

```
ANOVA Table (type II tests)

             Effect DFn DFd      F        p p<.05      ges
1        q_md_filled   1 301  0.177 6.74e-01       0.000589
2            Site_id   5 301 26.589 3.00e-22     * 0.306000
3 q_md_filled:Site_id   5 301  5.631 5.58e-05     * 0.086000
```

Is there a significant difference in the hydrological response of **CO2** concentrations between *Treatments or Sites*?

```
ANOVA Table (type II tests)

               Effect DFn DFd     F     p p<.05   ges
1          q_md_filled   1 115 6.981 0.009     * 0.057
2            Treatment   2 115 1.602 0.206       0.027
3 q_md_filled:Treatment   2 115 1.804 0.169       0.030
```

```
ANOVA Table (type II tests)

             Effect DFn DFd      F        p p<.05   ges
1        q_md_filled   1 109  7.711 6.00e-03     * 0.066
2            Site_id   5 109 20.742 1.64e-14     * 0.488
3 q_md_filled:Site_id   5 109  3.247 9.00e-03     * 0.130
```

Interpretation

DOC and CO2 concentrations are not controled by Discharge

- Q **doesn't** have a significant effect on DOC concentration, but treatment and site do (intercept difference). Significant interaction between Q and Site (slope difference)
- Q doesnt have a significant effect on CO2 concentration, nor does treatment. Site effect causes a signficant effect on intercept and slope (interaction)

3.3.2 Hydrological controls over ^{14}C-content

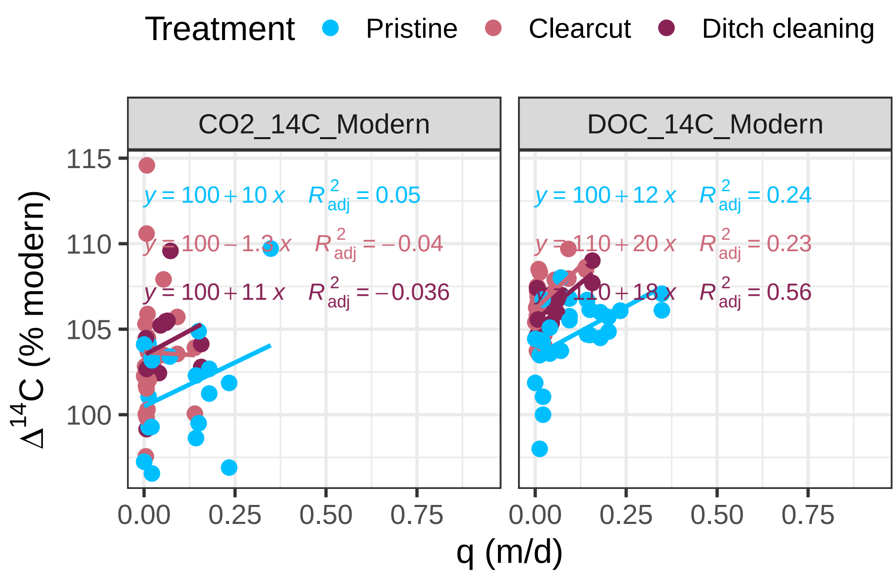

Figure 5: relationship between radiocarbon content of CO2 and DOC and discharge, coloured by treatment

3.3.2.1 ANCOVA test

Is there a significant difference in the hydrological response of **14C-DOC** between *Treatments*?

```
ANOVA Table (type II tests)

               Effect DFn DFd      F        p p<.05   ges
1          q_md_filled   1  62 24.164 6.81e-06     * 0.280
2            Treatment   2  62 22.767 3.86e-08     * 0.423
3 q_md_filled:Treatment   2  62  0.684 5.08e-01       0.022
```

Is there a significant difference in the hydrological response of **14C-CO2** between *Treatments*?

```
ANOVA Table (type II tests)

               Effect DFn DFd     F     p p<.05   ges
1          q_md_filled   1  52 1.816 0.184       0.034
2            Treatment   2  52 4.062 0.023     * 0.135
3 q_md_filled:Treatment   2  52 0.237 0.790       0.009
```

3.3.2.2 Linear mixed effect model

```
Call:
glm(formula = DOC_14C_Modern ~ q_md_filled * Treatment, data = DC_Q)

Coefficients:
                                     Estimate Std. Error t value Pr(>|t|)
(Intercept)                         1.034e+02  4.459e-01 231.992  < 2e-16 ***
q_md_filled                         1.156e+04  3.017e+03   3.834 0.000298 ***
TreatmentClearcut                   2.739e+00  5.805e-01   4.718  1.4e-05 ***
TreatmentDitch cleaning             2.063e+00  8.153e-01   2.530 0.013958 *
q_md_filled:TreatmentClearcut       8.617e+03  8.217e+03   1.049 0.298432
q_md_filled:TreatmentDitch cleaning 6.027e+03  9.444e+03   0.638 0.525695
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for gaussian family taken to be 2.491009)

    Null deviance: 281.24  on 67  degrees of freedom
Residual deviance: 154.44  on 62  degrees of freedom
  (4341 observations deleted due to missingness)
AIC: 262.76

Number of Fisher Scoring iterations: 2
```

3.3.2.3 ANCOVA test

Is there a significant difference in the hydrological response of **14C-DOC** between *Sites*?

```
ANOVA Table (type II tests)

               Effect DFn DFd      F        p p<.05   ges
1         q_md_filled   1  56 18.570 6.68e-05     * 0.249
2             Site_id   5  56  6.873 4.60e-05     * 0.380
3 q_md_filled:Site_id   5  56  1.194 3.24e-01       0.096
```

i Interpretation

- q has a significant effect on 14C-DOC, but not on 14C-CO2
- (LME) there is a significant effect of both **Treatment 14C-DOC** in the model (intercept differences), but no significant interaction (slope differences). No significant effect of Site_id

- The intercept shifts from 100%modern in pristine sites, to 110%modern in clearcut+ditchcleaned sites.
- Site_id explains only 13% of the variance (LME), not a significant predictor.

3.4 Biological controls over ^{14}C-CO_2 - Keeling plots

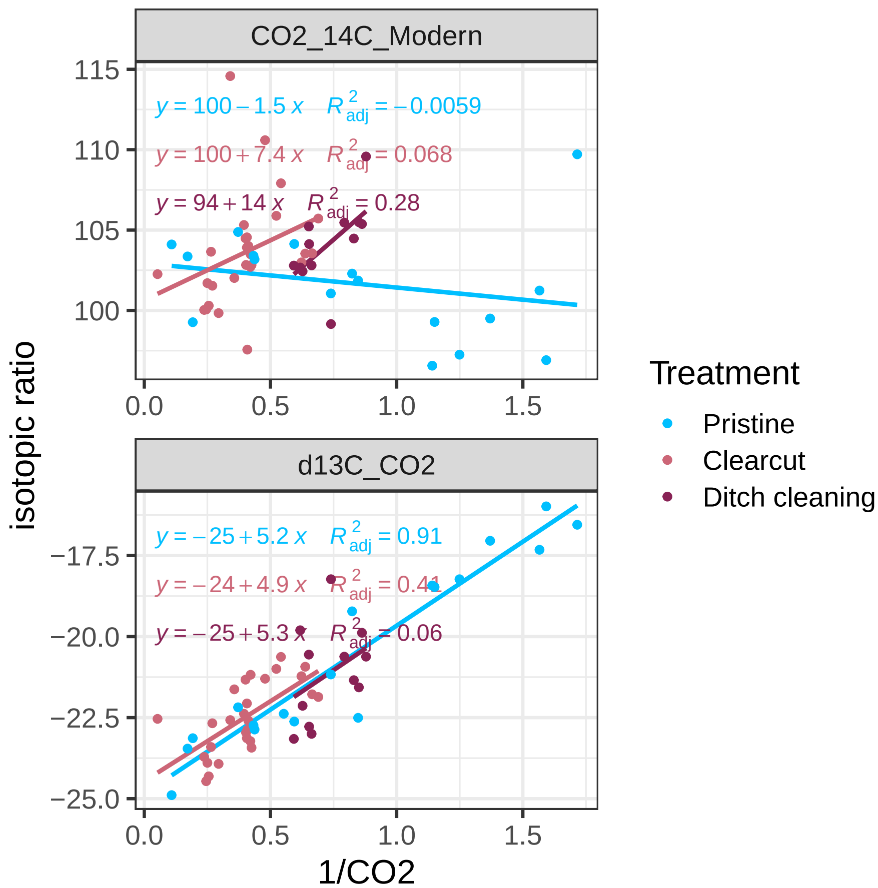

Figure 6: Keeling plot of CO2 isotope ratio, stable and radiogenic, coloured by treatment

3.4.0.1 ANCOVA test

Does the keeling relationship for **d13C-CO2** varies significantly between treatment?

```
ANOVA Table (type II tests)

                          Effect DFn DFd       F        p p<.05      ges
1            CO2_mgL_filled_keeling   1  51 145.233 1.53e-16     * 0.740000
2                        Treatment   2  51   0.527 5.93e-01       0.020000
3 CO2_mgL_filled_keeling:Treatment   2  51   0.018 9.83e-01       0.000687
```

Does the keeling relationship for **14C-CO2** varies significantly between treatment?

```
ANOVA Table (type II tests)

                          Effect DFn DFd     F     p p<.05      ges
1            CO2_mgL_filled_keeling   1  50 0.014 0.907       0.000277
2                        Treatment   2  50 2.409 0.100       0.088000
3 CO2_mgL_filled_keeling:Treatment   2  50 3.347 0.043     * 0.118000
```

Interpretation

- The keeling plot suggests that CO2 concentration has a significant effect on both d13C-value and 14C-concent, which supports the idea of a biological control.
- But this relationship doesn't change signficantly with treatment. Perhaps the sample size is not enough to identify a meaningful effect
- The d13C source of CO2 is (-25‰) (no signficant effect of slope or intercept across sites or treatment)
- The 14C source of CO2 is between 99, 100m and 94. Which are large differences, but don't appear as significant effects in the model.

Campeau, A., K. Bishop, N. Amvrosiadi, M. F. Billett, M. H. Garnett, H. Laudon, M. G. Öquist, and M. B. Wallin. 2019. "Current Forest Carbon Fixation Fuels Stream CO2 Emissions." *Nature Communications* 10 (1). https://doi.org/10.1038/s41467-019-09922-3.

Campeau, Audrey, Kevin H. Bishop, Michael F. Billett, Mark H. Garnett, Hjalmar Laudon, Jason A. Leach, Mats B. Nilsson, Mats G. Öquist, and Marcus B. Wallin. 2017. "Aquatic Export of Young Dissolved and Gaseous Carbon from a Pristine Boreal Fen: Implications for Peat Carbon Stock Stability." *Global Change Biology* 23 (12): 5523–36. https://doi.org/10.1111/gcb.13815.

Ledesma, J. L. J., T. Grabs, M. N. Futter, K. H. Bishop, H. Laudon, and S. J. Köhler. 2013. "Riparian Zone Control on Base Cation Concentration in Boreal Streams." *Biogeosciences* 10 (6): 3849–68. https://doi.org/10.5194/bg-10-3849-2013.

Öquist, M. G., K. Bishop, A. Grelle, L. Klemedtsson, S. J. Köhler, H. Laudon, A. Lindroth, M. Ottosson Löfvenius, M. B. Wallin, and M. B. Nilsson. 2014. "The Full Annual Carbon Balance of Boreal Forests Is Highly Sensitive to Precipitation." *Environmental Science & Technology Letters* 1 (7): 315–19. https://doi.org/10.1021/ez500169j.