**Valley-bottom wetland agricultural conversion and recovery shape greenhouse gas dynamics and soil carbon sequestration in an African tropical highland system.**

Supplementary material

Table S1: Descriptive statistical summary of GHG flux and soil properties from the intact, recovering and converted wetlands in the dry, wet and rewetting seasons.

| | | STATISTICS | $N_2O$-N flux | $CH_4$-C flux | $CO_2$-C flux | Soil temperature | Percentage water content | $NH_4^+$-N | $NO_3^-$-N | Phosphorous |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | (µg $m^{-2}$ h-1) | (mg $m^{-2}$ $h^{-1}$) | (mg $m^{-2}$ $h^{-1}$) | °C | % | (µg g-1) DW | (µg $g^{-1}$) DW | (µg N g-1) DW |
| **INTACT** | **DRY** | **No. of variables** | 18 | 17 | 20 | 20 | 11 | 11 | 11 | 9 |
| | | **Minimum** | -24.10 | 4.62 | 5.94 | 20.70 | 27.09 | 3.52 | 0.05 | 20.24 |
| | | **Maximum** | 29.50 | 87.65 | 109.31 | 40.00 | 52.94 | 96.84 | 1.92 | 194.71 |
| | | **Median** | -3.35 | 18.08 | 38.61 | 28.60 | 44.25 | 20.62 | 0.20 | 137.57 |
| | | **Mean** | -2.98 | 32.93 | 46.46 | 28.75 | 42.45 | 32.97 | 0.34 | 115.82 |
| | | **Standard Error Mean** | 2.37 | 7.26 | 6.41 | 1.06 | 3.19 | 8.16 | 0.16 | 21.93 |
| | | **Confidence Interval of the mean 95%** | 5.00 | 15.39 | 13.42 | 2.23 | 7.12 | 18.17 | 0.36 | 50.58 |
| | | **Variance** | 101.26 | 895.90 | 822.20 | 22.62 | 112.22 | 731.67 | 0.29 | 4329.88 |
| | | **Standard deviation** | 10.06 | 29.93 | 28.67 | 4.76 | 10.59 | 27.05 | 0.54 | 65.80 |
| | | **Coefficient of variance** | -3.37 | 0.91 | 0.62 | 0.17 | 0.25 | 0.82 | 1.57 | 0.57 |
| | **WET** | **STATISTICS** | **$N_2O$-N flux** | **$CH_4$-C flux** | **$CO_2$-C flux** | **Soil temperature** | **Percentage water content** | **$NH_4^+$-N** | **$NO_3^-$-N** | **Phosphorous** |
| | | **No. of variables** | 13 | 8 | 14 | 14 | 14 | 14 | 14 | 11 |
| | | **Minimum** | -38.10 | 6.25 | 7.20 | 24.00 | 27.09 | 3.52 | 0.18 | 57.07 |
| | | **Maximum** | 10.02 | 91.28 | 106.21 | 34.50 | 56.16 | 76.29 | 1.92 | 190.00 |
| | | **Median** | -0.87 | 24.19 | 16.08 | 28.65 | 50.81 | 58.52 | 0.77 | 121.38 |
| | | **Mean** | -6.19 | 40.58 | 30.84 | 29.13 | 46.95 | 51.74 | 0.96 | 131.56 |
| | | **Standard Error Mean** | 3.60 | 13.46 | 8.10 | 1.00 | 3.03 | 7.72 | 0.15 | 11.12 |
| | | **Confidence Interval of the mean 95%** | 7.85 | 31.82 | 17.50 | 2.16 | 6.55 | 16.67 | 0.33 | 24.79 |
| | | **Variance** | 168.94 | 1448.78 | 918.13 | 13.93 | 128.62 | 833.37 | 0.32 | 1361.09 |
| | | **Standard deviation** | 13.00 | 38.06 | 30.30 | 3.73 | 11.34 | 28.87 | 0.57 | 36.89 |
| | | **Coefficient of variance** | -2.10 | 0.94 | 0.98 | 0.13 | 0.24 | 0.56 | 0.59 | 0.28 |
| | **REWETTING** | **STATISTICS** | **$N_2O$-N flux** | **$CH_4$-C flux** | **$CO_2$-C flux** | **Soil temperature** | **Percentage water content** | **$NH_4^+$-N** | **$NO_3^-$-N** | **Phosphorous** |
| | | **No. of variables** | 8 | 6 | 8 | 8 | 8 | 8 | 8 | 8 |
| | | **Minimum** | -9.63 | 3.93 | 24.95 | 24.00 | 29.58 | 20.15 | 0.05 | 20.24 |
| | | **Maximum** | 11.52 | 36.81 | 162.40 | 30.50 | 53.29 | 138.76 | 0.64 | 211.20 |
| | | **Median** | -3.13 | 12.45 | 42.20 | 28.85 | 49.23 | 39.35 | 0.20 | 112.70 |
| | | **Mean** | -1.94 | 14.34 | 54.55 | 28.30 | 45.08 | 59.55 | 0.24 | 106.84 |
| | | **Standard Error Mean** | 2.11 | 4.89 | 15.91 | 0.89 | 3.48 | 15.77 | 0.07 | 24.27 |
| | | **Confidence Interval of the mean 95%** | 4.99 | 12.57 | 37.62 | 2.10 | 8.22 | 37.29 | 0.17 | 57.39 |
| | | **Variance** | 35.68 | 143.58 | 2025.34 | 6.33 | 96.63 | 1989.66 | 0.04 | 4711.78 |
| | | **Standard deviation** | 5.97 | 11.98 | 45.00 | 2.52 | 9.83 | 44.61 | 0.21 | 68.64 |
| | | **Coefficient of variance** | -3.08 | 0.84 | 0.82 | 0.09 | 0.22 | 0.75 | 0.86 | 0.64 |
| **RECOVE RING** | **DRY** | **STATISTICS** | **$N_2O$-N flux** | **$CH_4$-C flux** | **$CO_2$-C flux** | **Soil temperature** | **Percentage water content** | **$NH_4^+$-N** | **$NO_3^-$-N** | **Phosphorous** |
| | | **No. of variables** | 204 | 197 | 212 | 215 | 96 | 92 | 91 | 68 |
| | | **Minimum** | -27.85 | -7.27 | 17.52 | 17.57 | 14.68 | 0.54 | 0.03 | 4.45 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Maximum | 119.78 | 80.94 | 419.85 | 39.90 | 91.20 | 110.32 | 20.95 | 258.79 |
| | | Median | 0.62 | 5.08 | 128.98 | 26.75 | 53.58 | 11.04 | 0.72 | 20.81 |
| | | Mean | 3.01 | 11.11 | 145.72 | 26.92 | 54.75 | 17.70 | 1.66 | 37.16 |
| | | Standard Error Mean | 1.15 | 1.04 | 5.19 | 0.29 | 1.79 | 2.28 | 0.30 | 6.14 |
| | | Confidence Interval of the mean 95% | 2.27 | 2.06 | 10.23 | 0.57 | 3.56 | 4.53 | 0.59 | 12.26 |
| | | Variance | 270.65 | 214.46 | 5711.72 | 17.75 | 308.68 | 479.51 | 7.98 | 2564.17 |
| | | Standard deviation | 16.45 | 14.64 | 75.58 | 4.21 | 17.57 | 21.90 | 2.83 | 50.64 |
| | | Coefficient of variance | 5.47 | 1.32 | 0.52 | 0.16 | 0.32 | 1.24 | 1.70 | 1.36 |
| | | **STATISTICS** | **$N_2O$-N flux** | **$CH_4$-C flux** | **$CO_2$-C flux** | **Soil temperature** | **Percentage water content** | **$NH_4^+$-N** | **$NO_3^-$-N** | **Phosphorous** |
| | | No. of variables | 149 | 143 | 151 | 154 | 144 | 153 | 153 | 105 |
| | | Minimum | -38.88 | -6.14 | 2.73 | 13.80 | 27.06 | 1.04 | 0.08 | 1.83 |
| | | Maximum | 155.76 | 80.62 | 429.27 | 40.23 | 91.20 | 165.81 | 12.21 | 181.25 |
| | | Median | 2.83 | 2.03 | 116.33 | 25.70 | 46.58 | 12.62 | 0.91 | 14.45 |
| | WET | Mean | 9.05 | 9.25 | 125.50 | 26.08 | 51.90 | 19.93 | 1.87 | 23.91 |
| | | Standard Error Mean | 1.75 | 1.26 | 6.19 | 0.34 | 1.43 | 2.05 | 0.18 | 2.68 |
| | | Confidence Interval of the mean 95% | 3.46 | 2.49 | 12.23 | 0.68 | 2.83 | 4.05 | 0.37 | 5.30 |
| | | Variance | 457.41 | 226.72 | 5782.37 | 18.00 | 294.33 | 643.24 | 5.23 | 751.41 |
| | | Standard deviation | 21.39 | 15.06 | 76.04 | 4.24 | 17.16 | 25.36 | 2.29 | 27.41 |
| | | Coefficient of variance | 2.36 | 1.63 | 0.61 | 0.16 | 0.33 | 1.27 | 1.22 | 1.15 |
| | | **STATISTICS** | **$N_2O$-N flux** | **$CH_4$-C flux** | **$CO_2$-C flux** | **Soil temperature** | **Percentage water content** | **$NH_4^+$-N** | **$NO_3^-$-N** | **Phosphorous** |
| | | No. of variables | 68 | 65 | 69 | 71 | 67 | 67 | 61 | 59 |
| | | Minimum | -31.60 | -0.49 | 27.91 | 17.67 | 20.81 | 0.54 | 0.03 | 1.59 |
| | | Maximum | 262.79 | 69.64 | 433.03 | 32.90 | 88.50 | 105.38 | 32.23 | 160.09 |
| | | Median | -1.34 | 7.12 | 106.26 | 24.00 | 45.66 | 9.46 | 0.77 | 18.59 |
| | REWETTING | Mean | 5.04 | 11.11 | 116.62 | 24.35 | 50.40 | 17.12 | 2.57 | 29.62 |
| | | Standard Error Mean | 4.21 | 1.76 | 8.52 | 0.44 | 1.85 | 2.70 | 0.66 | 3.94 |
| | | Confidence Interval of the mean 95% | 8.39 | 3.51 | 17.00 | 0.88 | 3.69 | 5.39 | 1.33 | 7.88 |
| | | Variance | 1202.70 | 200.40 | 5009.21 | 13.76 | 228.34 | 488.87 | 26.91 | 915.01 |
| | | Standard deviation | 34.68 | 14.16 | 70.78 | 3.71 | 15.11 | 22.11 | 5.19 | 30.25 |
| | | Coefficient of variance | 6.88 | 1.27 | 0.61 | 0.15 | 0.30 | 1.29 | 2.02 | 1.02 |
| | | **STATISTICS** | **$N_2O$-N flux** | **$CH_4$-C flux** | **$CO_2$-C flux** | **Soil temperature** | **Percentage water content** | **$NH_4^+$-N** | **$NO_3^-$-N** | **Phosphorous** |
| | | No. of variables | 303 | 295 | 308 | 308 | 135 | 131 | 138 | 111 |
| | | Minimum | -21.41 | -2.45 | 6.80 | 17.33 | 3.05 | 0.05 | 0.11 | 6.06 |
| | | Maximum | 470.76 | 27.00 | 531.00 | 43.00 | 49.57 | 42.62 | 98.50 | 249.13 |
| | | Median | 5.63 | -0.01 | 123.99 | 29.40 | 28.25 | 4.37 | 10.35 | 23.24 |
| CONVERTED | DRY | Mean | 20.30 | 0.54 | 134.04 | 29.56 | 26.99 | 7.22 | 16.21 | 38.69 |
| | | Standard Error Mean | 2.67 | 0.16 | 3.85 | 0.28 | 0.86 | 0.68 | 1.76 | 3.63 |
| | | Confidence Interval of the mean 95% | 5.26 | 0.32 | 7.58 | 0.56 | 1.69 | 1.35 | 3.48 | 7.20 |
| | | Variance | 2163.44 | 7.98 | 4571.66 | 24.56 | 99.11 | 61.29 | 427.41 | 1463.86 |
| | | Standard deviation | 46.51 | 2.82 | 67.61 | 4.96 | 9.96 | 7.83 | 20.67 | 38.26 |
| | | Coefficient of variance | 2.29 | 5.23 | 0.50 | 0.17 | 0.37 | 1.09 | 1.28 | 0.99 |

| | STATISTICS | $N_2O$-N flux | $CH_4$-C flux | $CO_2$-C flux | Soil temperature | Percentage water content | $NH_4^+$-N | $NO_3^-$-N | Phosphorous |
|---|---|---|---|---|---|---|---|---|---|
| WET | No. of variables | 183 | 189 | 195 | 199 | 189 | 197 | 200 | 138 |
| | Minimum | -27.33 | -1.27 | 7.64 | 18.23 | 5.98 | 1.29 | 0.02 | 1.87 |
| | Maximum | 359.87 | 26.71 | 423.23 | 38.70 | 55.83 | 41.93 | 94.15 | 157.27 |
| | Median | 12.04 | 0.00 | 136.01 | 27.47 | 30.48 | 3.97 | 7.80 | 23.12 |
| | Mean | 29.62 | 0.45 | 146.27 | 27.89 | 30.22 | 6.58 | 10.23 | 39.30 |
| | Standard Error Mean | 3.89 | 0.21 | 5.49 | 0.33 | 0.63 | 0.48 | 0.87 | 3.30 |
| | Confidence Interval of the mean 95% | 7.68 | 0.41 | 10.83 | 0.66 | 1.24 | 0.95 | 1.71 | 6.53 |
| | Variance | 2774.82 | 8.30 | 5879.22 | 21.97 | 74.86 | 46.09 | 151.26 | 1506.01 |
| | Standard deviation | 52.68 | 2.88 | 76.68 | 4.69 | 8.65 | 6.79 | 12.30 | 38.81 |
| | Coefficient of variance | 1.78 | 6.42 | 0.52 | 0.17 | 0.29 | 1.03 | 1.20 | 0.99 |
| | STATISTICS | $N_2O$-N flux | $CH_4$-C flux | $CO_2$-C flux | Soil temperature | Percentage water content | $NH_4^+$-N | $NO_3^-$-N | Phosphorous |
| REWETTING | No. of variables | 81 | 82 | 83 | 84 | 83 | 78 | 84 | 76 |
| | Minimum | -6.03 | -0.03 | 20.18 | 16.90 | 5.96 | 0.05 | 0.32 | 3.64 |
| | Maximum | 585.75 | 7.69 | 334.64 | 33.77 | 42.34 | 34.13 | 97.67 | 134.11 |
| | Median | 7.11 | 0.00 | 126.50 | 25.55 | 27.89 | 1.86 | 14.93 | 29.51 |
| | Mean | 73.98 | 0.35 | 130.52 | 25.58 | 26.85 | 4.13 | 20.70 | 37.64 |
| | Standard Error Mean | 16.72 | 0.13 | 6.94 | 0.43 | 1.08 | 0.65 | 2.25 | 3.72 |
| | Confidence Interval of the mean 95% | 33.27 | 0.26 | 13.81 | 0.86 | 2.15 | 1.30 | 4.47 | 7.40 |
| | Variance | 22634.21 | 1.39 | 3999.27 | 15.60 | 96.96 | 33.26 | 423.98 | 1048.98 |
| | Standard deviation | 150.45 | 1.18 | 63.24 | 3.95 | 9.85 | 5.77 | 20.59 | 32.39 |
| | Coefficient of variance | 2.03 | 3.39 | 0.48 | 0.15 | 0.37 | 1.39 | 0.99 | 0.86 |

Table S2: Table showing sampling sites with their vegetation cover, land use history, and altitude. Time since conversion was derived from Gubamwoyo et al. (2025).

| Site ID | Site name | Wetland type | Time since conversion | Dominant vegetation | Altitude (m.a.s.l) |
|---|---|---|---|---|---|
| 1. | Mwatate | Intact | 0 | *Typha latifolia* | 850.6 |
| 2. | Mwatate | Converted | 40 | Maize | 830.7 |
| 3. | Wesu | Recovering | 5 | *Cyperus odoratus* | 1608.6 |
| 4. | Wesu | Converted | 70 | Maize and beans | 1594.9 |
| 5. | Ngilinyi | Converted | 50 | Kales | 1288.1 |
| 6. | Ngilinyi | Recovering | 5 | *Cyperus odoratus* | 1302.2 |
| 7. | Ngelenyi | Converted | 40 | Maize and beans | 1549.1 |
| 8. | Ngelenyi | Recovering | 5 | *Royal ferns* | 1560.3 |
| 9. | Kirwenyi | Converted | 50 | Kales and maize | 1437.5 |
| 10. | Kirwenyi | Recovering | 10 | *Cyperus odoratus* | 1432.1 |
| 11. | Irido | Converted | 30 | Maize and beans | 1407.4 |
| 12. | Irido | Recovering | 10 | *Cyperus odoratus* | 1407.1 |
| 13. | Maringo | Converted | 30 | Maize and vegetables | 1536.1 |
| 14. | Maringo | Recovering | 10 | *Cyperus odoratus* | 1533.1 |
| 15. | Water pump | Converted | 60 | Maize and beans | 1415 |
| 16. | Water pump | Recovering | 10 | *Cyperus odoratus* | 1406 |
| 17. | Lushangonyi | Converted | 60 | Maize and beans | 1601.9 |
| 18. | Lushangonyi | Recovering | 10 | *Cyperus odoratus* | 1605.7 |
| 19. | Lunonyi | Recovering | 10 | *Cyperus odoratus* | 1586.4 |
| 20. | Wundanyi | Converted | 70 | Maize, beans and vegetables | 1399 |
| 21. | Munuka | Converted | 50 | Kales and spinach | 1650.6 |
| 22. | Kimangachugu | Converted | 40 | Kales | 1602.7 |
| 23. | Kimangachugu | Recovering | 5 | *Royal ferns* | 1608.8 |

Time since conversion: 0 indicates no conversion at all (intact HVBW), five and ten are recovering HVBW where five indicates recovering HVBW that have been left abandoned for 50 years and above, ten indicates HVBW that have been abandoned for less than 50 years. 30 – 70 indicates the years the HVBW has been under cultivation.

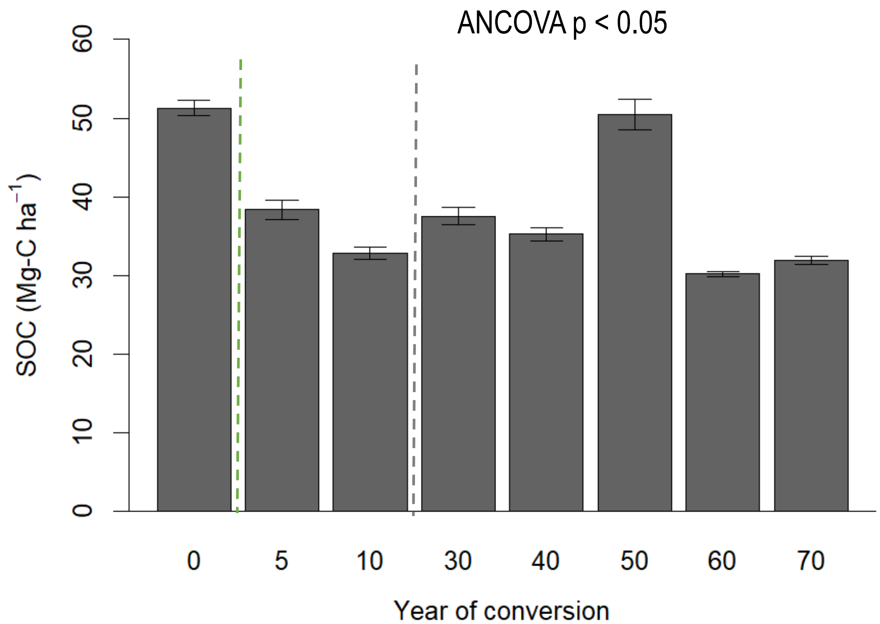


**Figure S1:** SOC variation by years of HVBW conversion. The green line indicates the boundary of the intact HVBW and the grey line indicates the boundary of the recovering HVBW. 0 indicates no conversion at all (intact HVBW), five and ten are recovering HVBW where five indicates recovering HVBW that have been left abandoned for 50 years and above, ten indicates HVBW that have been abandoned for less than 50 years. 30 – 70 bars indicated the years the HVBW has been under cultivation

Figure S2: Photo showing (L-R) Intact HVBW, Recovering HVBW and Converted HVBW in Taita Hills.

Figure S3: Photo showing floating chambers and the wooden walkway to enable GHG sampling in the intact HVBW


Figure S4: Photo showing the GHG chambers describing the different parts and components of the chamber.

$$SOC = BD \times \%C \times sd$$

Equation 1

Where SOC is the soil organic carbon stock at a fixed depth (Mg C $ha^{-1}$), BD is the bulk density (g $cm^{-3}$), %C is the percentage carbon measured in the lab which is converted into mg $g^{-1}$, sd is the soil depth segment (cm), the conversion of the units are handled within the calculation.

BD

%C is converted into mg $g^{-1}$ by multiplying by 10

$$SOC = \frac{g}{cm3}$$

The reduction in bulk density (BD) with decreased disturbance and rising soil organic carbon (SOC), assuming SOC and BD remain constant within this depth range, leads to inaccurate SOC stock estimates. While the equivalent soil mass (ESM) method addresses this fixed depth error, its adoption remains limited. We examine SOC stock evaluation inaccuracies caused by fixed depth versus ESM methods.

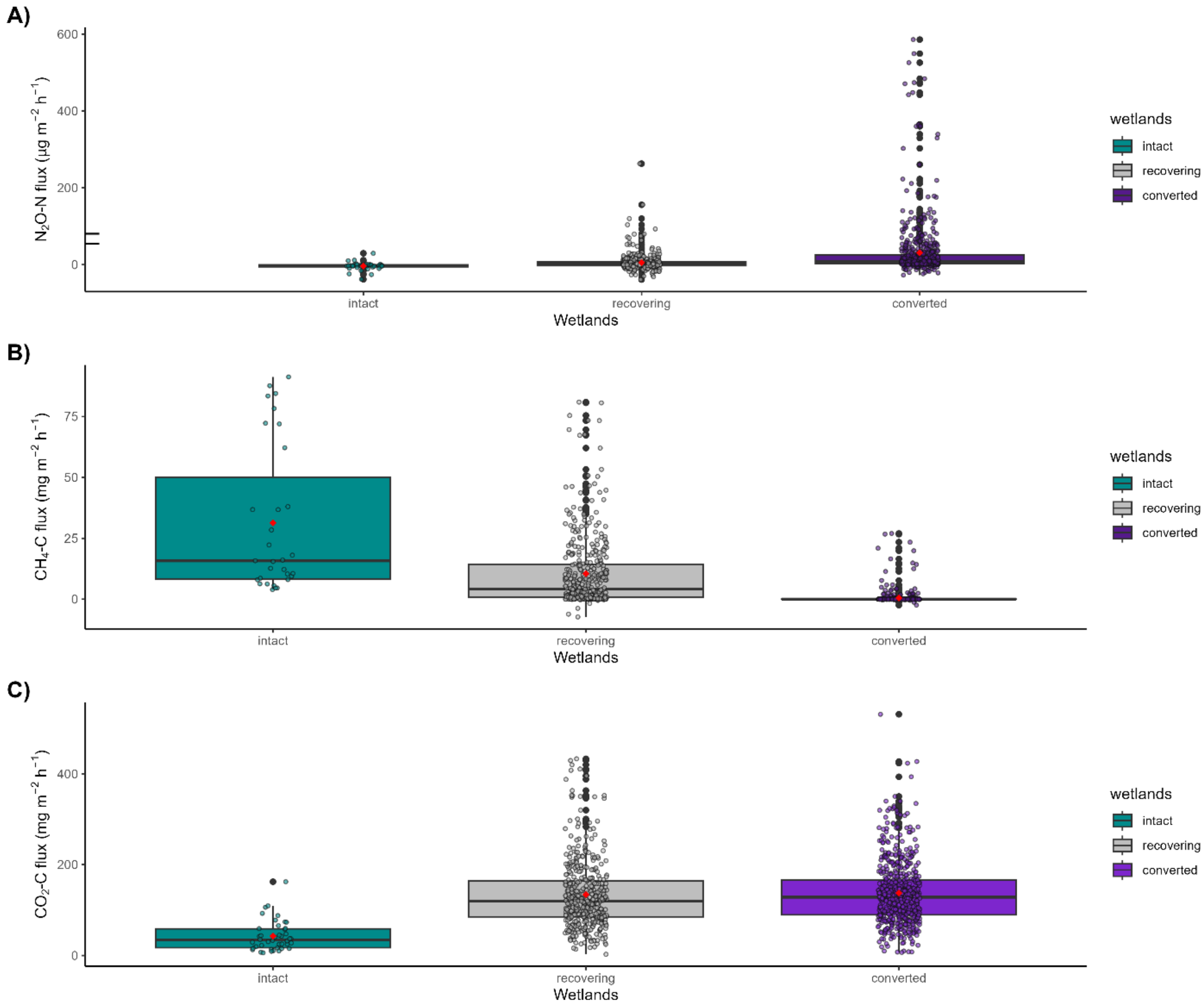


Figure S5: Boxplots showing GHG variations by wetland type for the whole study period. (intact refers to HVBWS that have never been used for agriculture n = 1; recovering refers to HVBWS that were once converted to cropland but abandoned n = 10; converted refers to drained wetlands currently in use for crop production n = 12). The boxes represent the interquartile range (IQR), the horizontal line indicates the median and the whiskers extend to 1.5 x IQR. The points outside the line represent outliers.

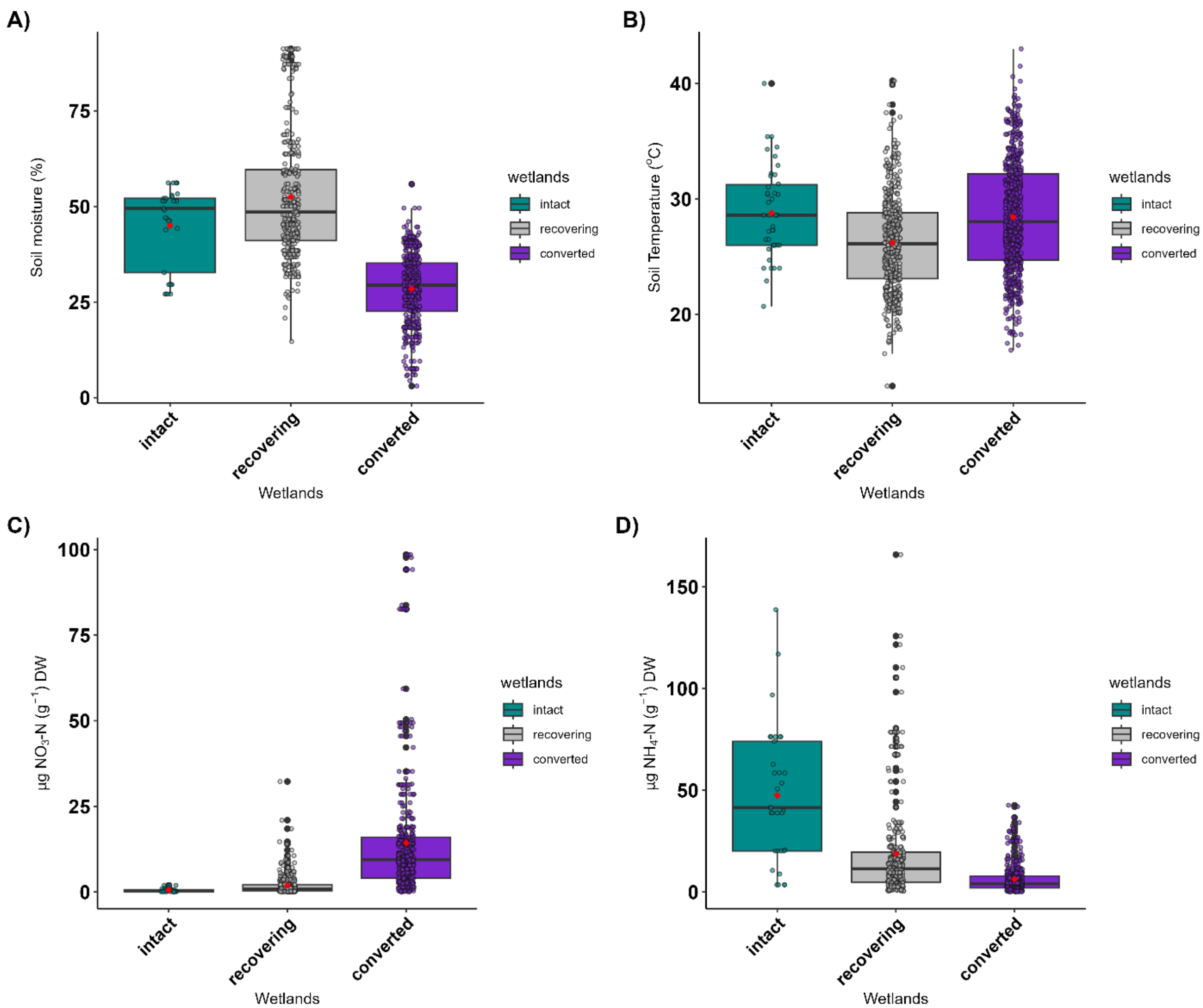


Figure S6: Boxplots showing soil characteristic variations by wetland type for the whole study period. (intact refers to HVBWS that have never been used for agriculture n = 1; recovering refers to HVBWS that were once converted to cropland but abandoned n = 10; converted refers to drained wetlands currently in use for crop production n = 12). The boxes represent the interquartile range (IQR), the horizontal line indicates the median and the whiskers extend to 1.5 x IQR. The points outside the line represent outliers.

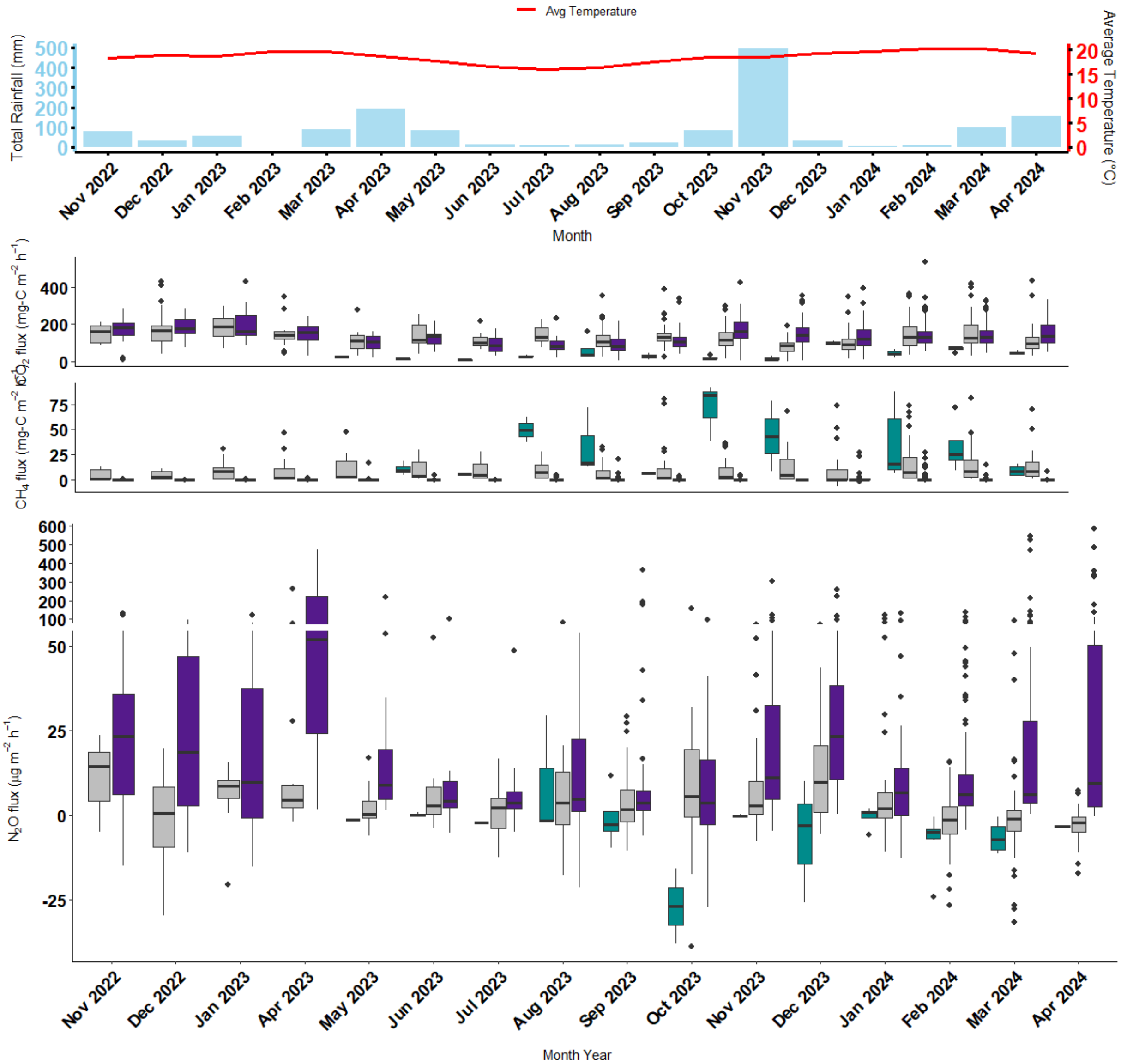


Figure S7: Boxplots showing GHG fluxes in the different HVBWs types by month for the whole study period indicating the monthly total rainfall and average temperature. (intact refers to HVBWS that have never been used for agriculture n = 1; recovering refers to HVBWS that were once converted to cropland but abandoned n = 10; converted refers to drained wetlands currently in use for crop production n = 12). The boxes represent the interquartile range (IQR), the horizontal line indicates the median and the whiskers extend to 1.5 x IQR. The points outside the line represent outliers.

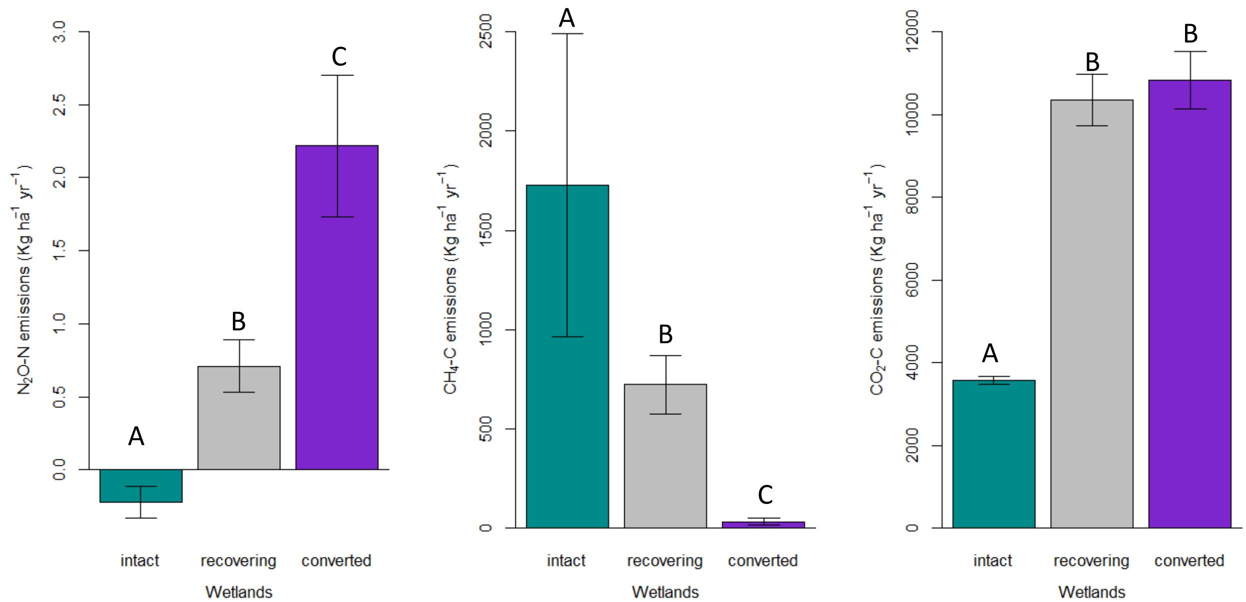


Figure S8: Bar graphs showing the average cumulative GHG emissions with error bars from the HVBW for one year. The upper-case letters indicate statistically significant differences ($p < 0.05$) between wetland types.