Potential of biochar to reduce greenhouse gas emissions and increase nitrogen use efficiency in boreal arable soils in the long-term

Supplementary materials

# Supplementary Tables

Supplementary Table S1. Monthly precipitation and mean air temperature during the growing season 2018 compared with the long-term average from 1981–2010 (FMI, 2020). The long-term average data for Viikki, Qvidja, and Jokioinen were obtained from the weather data of Helsinki, Turku and Hämeenlinna, respectively, from Finnish Meteorological Institute (FMI) website (https://en.ilmatieteenlaitos.fi/normal-period-1981-2010). The 2018 weather data for Viikki and Jokioinen are recorded from the stations of FMI at Kumpula and Jokioinen Ilmala respectively, whereas the 2018 weather data for Qvidja was recorded at on-site.

|  |  |  |  |
| --- | --- | --- | --- |
| **Month** | **Precipitation (mm)** |  | **Temperature (°C)** |
| **2018** | **Long-term average from 1981–2010** | **Difference from the long-term average (%)** |  | **2018** | **Long-term average from 1981–2010** | **Difference from the long-term average (%)** |
| Viikki |  |  |  |  |  |  |  |
| May | 8 | 37 | -79 |  | 15.0 | 9.5 | 58 |
| June | 37 | 56 | -34 |  | 15.6 | 14.1 | 11 |
| July | 37 | 62 | -40 |  | 21.3 | 17.4 | 22 |
| August | 62 | 78 | -20 |  | 18.6 | 16.2 | 15 |
| September | 68 | 56 | 22 |  | 13.6 | 11.5 | 18 |
| Qvidja |  |  |  |  |  |  |  |
| May | 18 | 38 | -54 |  | 15.2 | 10.0 | 52 |
| June | 19 | 56 | -66 |  | 15.3 | 14.4 | 6 |
| July | 61 | 77 | -21 |  | 21.4 | 17.4 | 23 |
| August | 42 | 79 | -47 |  | 18.3 | 16.0 | 14 |
| September | 80 | 63 | 27 |  | 13.8 | 11.1 | 24 |
| Jokioinen |  |  |  |  |  |  |  |
| May | 23 | 40 | -44 |  | 14.6 | 10.0 | 46 |
| June | 55 | 66 | -17 |  | 14.6 | 14.3 | 2 |
| July | 37 | 78 | -53 |  | 20.3 | 17.0 | 19 |
| August | 41 | 75 | -45 |  | 16.8 | 15.0 | 12 |
| September | 70 | 53 | 32 |  | 12.1 | 9.9 | 22 |

*The daily precipitation and mean air temperature are presented in Supplementary Figure S1.*

**Supplementary Table S2**. The summary of the statistics from linear mixed effects models on GHG fluxes. The results are presented in Figure 1.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Field** |  | **CO2** |  | **N2O** |  | **CH4** |
|  |  | **F** | **p-value** |  | **F** | **p-value** |  | **F** | **p-value** |
| **Jokioinen** | Treat | *2.35* | *0.131* |  | *0.76* | *0.131* |  | 0.07 | 0.796 |
|  | Time | *158.36* | ***<0.001*** |  | *11.74* | ***<0.001*** |  | 0.53 | 0.780 |
|  | Treat $×$ Time | *0.49* | *0.812* |  | *0.61* | *0.813* |  | 0.80 | 0.576 |
| **Qvidja** | Treat | *2.86* | ***0.049*** |  | *2.91* | ***0.047*** |  | *1.06* | *0.377* |
|  | Time | *42.59* | ***<0.001*** |  | *1.86* | *0.124* |  | *0.54* | *0.744* |
|  | Treat $×$ Time | *0.82* | *0.6517* |  | *0.42* | *0.963* |  | *0.93* | *0.537* |
| **Viikki-1** | Treat | *0.15* | *0.704* |  | 1.80 | 0.186 |  | *0.51* | *0.479* |
| Time | *96.61* | ***<0.001*** |  | 1.63 | 0.151 |  | *1.06* | *0.403* |
| Treat $×$ Time | *0.46* | *0.861* |  | 1.85 | 0.100 |  | *1.49* | *0.194* |
| **Viikki-2** | Treat | 9.38 | **0.004** |  | *0.16* | *0.695* |  | *0.58* | *0.451* |
| Time | 56.03 | **<0.001** |  | *8.29* | ***<0.001*** |  | *3.17* | ***0.008*** |
| Treat $×$ Time | 2.17 | 0.055 |  | *0.78* | *0.605* |  | *0.63* | *0.728* |

Box-Cox transformation was applied for the results reported in *italics*. The significant result (p < 0.05) was reported in **bold**.

**Supplementary Table S3**. The fluxes of GHG (average ± SE) averaged over the growing season 2018.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Fields** | **Treatments** | **CO2 (g C m-2 d-1)** | **CH4 (mg C m-2 d-1)** | **N2O (mg N m-2 d-1)** |
| Jokioinen | Control | 5.56 ± 0.66 | -0.06 ± 0.91 | 1.19 ± 0.39 |
|  | Biochar | 5.91 ± 0.70 | -0.01 ± 0.93 | 1.60 ± 0.45 |
| Qvidja | Unfertilized control | 20.27 ± 2.70 a | 0.15 ± 0.34 | 0.96 ± 0.26 |
|  | Fertilized control | 21.19 ± 2.54 ab | -0.13 ± 0.40 | 4.79 ± 2.05 |
|  | Spruce biochar | 26.14 ± 3.31 b | 0.67 ± 0.97 | 1.93 ± 0.58 |
|  | Willow biochar | 26.01 ± 3.56 ab | -0.80 ± 0.40 | 0.71 ± 0.19 |
| Viikki-1 | Control | 6.89 ± 0.78 | 0.05 ± 0.16 | 0.35 ± 0.10 |
|  | Biochar | 6.72 ± 0.75 | -0.10 ± 0.17 | 0.19 ± 0.07 |
| Viikk-2 | Control | 5.53 ± 0.41 a | 1.05 ± 0.43 | 0.72 ± 0.14 |
|  | Biochar | 6.28 ± 0.52 b | 0.67 ± 0.33 | 0.68 ± 0.12 |

Different letters among the treatments (if present) represent statistical difference between the treatments (p < 0.05).

**Supplementary Table S4**. The summary of the statistics from linear mixed effects models on cumulative GHG emission, GWP and GHGI. The mean values are presented in Table 3.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Field** | **Cumulative GHG Emissions** | **Crop yield****(t ha**−**)** | $$GWP$$**(kg CO2** – **e ha**−**1)** | **GHGI****(kg CO2** – **e t**−**1 grain)** |
| **g CO2**–**C m**−**2**  | **mg CH4**–**C m**−**2** | **mg N2O**–**N m**−**2** |
| **F** | **p-value** | **F** | **p-value** | **F** | **p-value** | **F** | **p-value** | **F** | **p-value** | **F** | **p-value** |
| **Jokioinen** | 0.98 | 0.378 | 0.08 | 0.792 | 0.56 | 0.493 | 1.72 | 0.259 | 0.93 | 0.388 | 0.55 | 0.499 |
| **Qvidja** | 4.30 | **0.060 ϯ** | 1.05 | 0.421 | 1.54 | 0.276 | 6.26 | **0.028** | 1.51 | 0.304 | 2.57 | 0.149 |
| **Viikki – 1** | 0.41 | 0.569 | 0.08 | 0.790 | 1.67 | 0.286 | 0.16 | 0.701 | 1.57 | 0.298 | 1.47 | 0.311 |
| **Viikki - 2** | 4.45 | 0.125 | 1.49 | 0.309 | 0.004 | 0.952 | 8.80 | **0.025** | 0.005 | 0.944 | *24.80* | ***0.015*** |

Box-Cox transformation was applied for the results reported in *italics*. The statistically significant result (p < 0.05) was reported in **bold**.

ϯ Statistical significance at p < 0.1.

**Supplementary Table S5**. The summary of the statistics from linear mixed effects models on microbial biomass carbon (MBC) and nitrogen (MBN), soil mineral N and mineral N leaching. The results are presented in Figure 2 and Figure 3.

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | **MBC** |  | **MBN** |  | **Soil NH4+–N** |  | **Soil NO3−–N** |  | **NH4+–N Leaching** |  | **NO3−–N Leaching** |
| **Field** |  | **F** | **p-value** |  | **F** | **p-value** |  | **F** | **p-value** |  | **F** | **p-value** |  | **F** | **p-value** |  | **F** | **p-value** |
| **Jokioinen** | Treat | 0.13 | 0.724 |  | 0.99 | 0.329 |  | *1.18* | *0.289* |  | 0.08 | 0.785 |  |  |  |  |  |  |
|  | Time | 11.35 | **<0.001** |  | 2.38 | 0.118 |  | *1.19* | *0.324* |  | 4.85 | **0.019** |  |  |  |  |  |  |
|  | Treat $×$ Time | 0.59 | 0.565 |  | 1.07 | 0.361 |  | *0.12* | *0.888* |  | 0.97 | 0.395 |  |  |  |  |  |  |
| **Qvidja** | Treat | *0.92* | *0.440* |  | *2.94* | ***0.049*** |  | *21.19* | ***<0.001*** |  | *52.81* | ***<0.001*** |  | *2.65* | *0.073* |  | 9.81 | **<0.001** |
|  | Time | *22.04* | ***<0.001*** |  | *4.87* | ***0.008*** |  | *30.29* | ***<0.001*** |  | *36.20* | ***<0.001*** |  | *0.37* | *0.696* |  | 11.69 | **<0.001** |
|  | Treat $×$ Time | *0.55* | *0.863* |  | *0.49* | *0.871* |  | *5.38* | ***<0.001*** |  | *2.42* | ***0.019*** |  | *1.62* | *0.189* |  | 4.04 | **0.007** |
| **Viikki – 1** | Treat | *11.70* | ***0.004*** |  | 2.22 | 0.344 |  | *2.75* | *0.118* |  | *0.23* | *0.635* |  |  |  |  |  |  |
| Time | *56.54* | ***<0.001*** |  | 55.12 | **<0.001** |  | *43.55* | ***<0.001*** |  | *58.34* | ***<0.001*** |  |  |  |  |  |  |
| Treat $×$ Time | *7.52* | ***0.006*** |  | 4.37 | **0.032** |  | *0.35* | *0.709* |  | *0.41* | *0.669* |  |  |  |  |  |  |
| **Viikki - 2** | Treat | 0.003 | 0.958 |  | 0.49 | 0.493 |  | *0.12* | *0.735* |  | 8.83 | **0.009** |  |  |  |  |  |  |
| Time | 36.84 | **<0.001** |  | 53.29 | **<0.001** |  | *43.84* | ***<0.001*** |  | 83.22 | **<0.001** |  |  |  |  |  |  |
| Treat $×$ Time | 1.67 | 0.221 |  | 1.79 | 0.199 |  | *2.03* | *0.166* |  | 4.12 | **0.037** |  |  |  |  |  |  |

Box-Cox transformation was applied for the results reported in *italics*. The significant results (p < 0.05) were reported in **bold**.

Supplementary Table S6. Microbial biomass carbon (MBC) and nitrogen (MBN), soil mineral N contents and mineral N leaching averaged over the growing season

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Fields**  | **Treatment** | **MBC****(mg C kg–1)** | **MBN****(mg N kg–1)** | **Soil NH4+–N****(mg N kg–1)** | **Soil NO3−–N****(mg N kg–1)** | **NH4+–N Leaching****(mg N kg–1)** | **NO3−–N Leaching****(mg N kg–1)** |
| Jokioinen | Control | 316.49 ± 21.44 | 23.96 ± 1.88 | 3.73 ± 0.74 | 11.78 ± 1.23 |  |  |
|  | Biochar | 307.18 ± 18.26 | 26.43 ± 2.34 | 4.81 ± 1.73 | 12.19 ± 1.6 |  |  |
| Qvidja | Unfertilized control | 166.17 ± 10.93 | 22.87 ± 1.78 | **1.05 ± 0.12 a** | **2.89 ± 0.47 a** | 0.09 ± 0.01 | **10.74 ± 1.06 a** |
|  | Fertilized control | 185.60 ± 16.32 | 27.08 ± 3.76 | **14.93 ± 6.54 b** | **17.78 ± 4.29 b** | 0.23 ± 0.05 | **72.44 ± 7.13 b** |
|  | Spruce biochar | 187.70 ± 12.04 | 28.91 ± 1.51 | **5.62 ± 1.85 b** | **21.46 ± 3.09 c** | 0.48 ± 0.25 | **28.12 ± 3.02 a** |
|  | Willow biochar | 180.22 ± 13.25 | 30.49 ± 1.91 | **11.43 ± 5.91 b** | **14.85 ± 3.28 b** | 0.19 ± 0.05 | **35.04 ± 2.71 a** |
| Viikki-1 | Control | 177.50 ± 19.14 b | 20.73 ± 1.57 | 3.14 ± 1.14 | 6.00 ± 1.17 |  |  |
|  | Biochar | 143.32 ± 10.04 a | 19.72 ± 1.95 | 2.31 ± 0.79 | 7.03 ± 1.76 |  |  |
| Viikki-2 | Control | 101.41 ± 13.58 | 11.56 ± 1.42 | 3.61 ± 0.80 | 7.12 ± 0.84 b |  |  |
|  | Biochar | 99.26 ± 12.23 | 11.03 ± 1.16 | 2.59 ± 0.30 | 5.70 ± 0.56 a |  |  |

Different letters among the treatments (if present) represent statistical difference among the treatments (p < 0.05).

**Supplementary Table S7**. The summary of the statistics from linear mixed effects models on cumulative N leaching, plant N uptake, N content, total plant biomass and N use efficiency (NUE) in Qvidja field. The mean values are presented in Table 4.

|  |  |  |
| --- | --- | --- |
|  | **F** | **p-value** |
| Cumulative NH4+–N leaching | 2.31 | 0.176 |
| Cumulative NO3−–N leaching | 5.38 | **0.038** |
| Plant N content | 1.71 | 0.262 |
| Total plant biomass | 6.73 | **0.024** |
| N uptake | 13.02 | **0.004** |
| NUE | 8.69 | **0.035** |

The significant results (p < 0.05) were reported in **bold**.

**Supplementary Table S8**. Pearson correlation between the relative differences in emissions of GHG between biochar and fertilized control treatments, and soil and biochar properties

|  |  |
| --- | --- |
|  | **Relative difference in:** |
|  | **CO2 emissions** | **CH4 emissions** | **N2O emissions** |
| **Sand (%)** | -0.100 | -0.044 | 0.143 |
| **Silt (%)** | 0.186 | 0.051 | **-0.583 \*\*** |
| **Clay (%)** | 0.063 | 0.037 | 0.005 |
| **Soil C (mg kg**−**1)** | -0.326 | -0.059 | **0.632 \*\*** |
| **Biochar pH** | -0.331 | -0.252 | -0.395 |
| **Biochar C (%)** | 0.073 | 0.362 | 0.022 |
| **Biochar C:N** | 0.235 | 0.349 | 0.097 |

\*\* The correlation was significant at P < 0.01. n = 19

# Supplementary Figures

**Supplementary Figure S1**. Daily precipitation (mm) and mean air temperature (°C) at Qvidja (a), Jokioinen (b) and Viikki (c) fields between May 15 and Sep 30 in 2018. The periods of N leaching measurements are marked for Qvidja field. The weather data for Viikki and Jokioinen were recorded from the stations of Finnish Meteorological Institute at Kumpula and Jokioinen Ilmala, respectively (FMI, 2020). The weather data for Qvidja were recorded from on-site weather station (Heimsch et al. 2021).

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