

## Supplementary Materials for

### **Carbon neutral expansion of oil palm plantations in the Neotropics**

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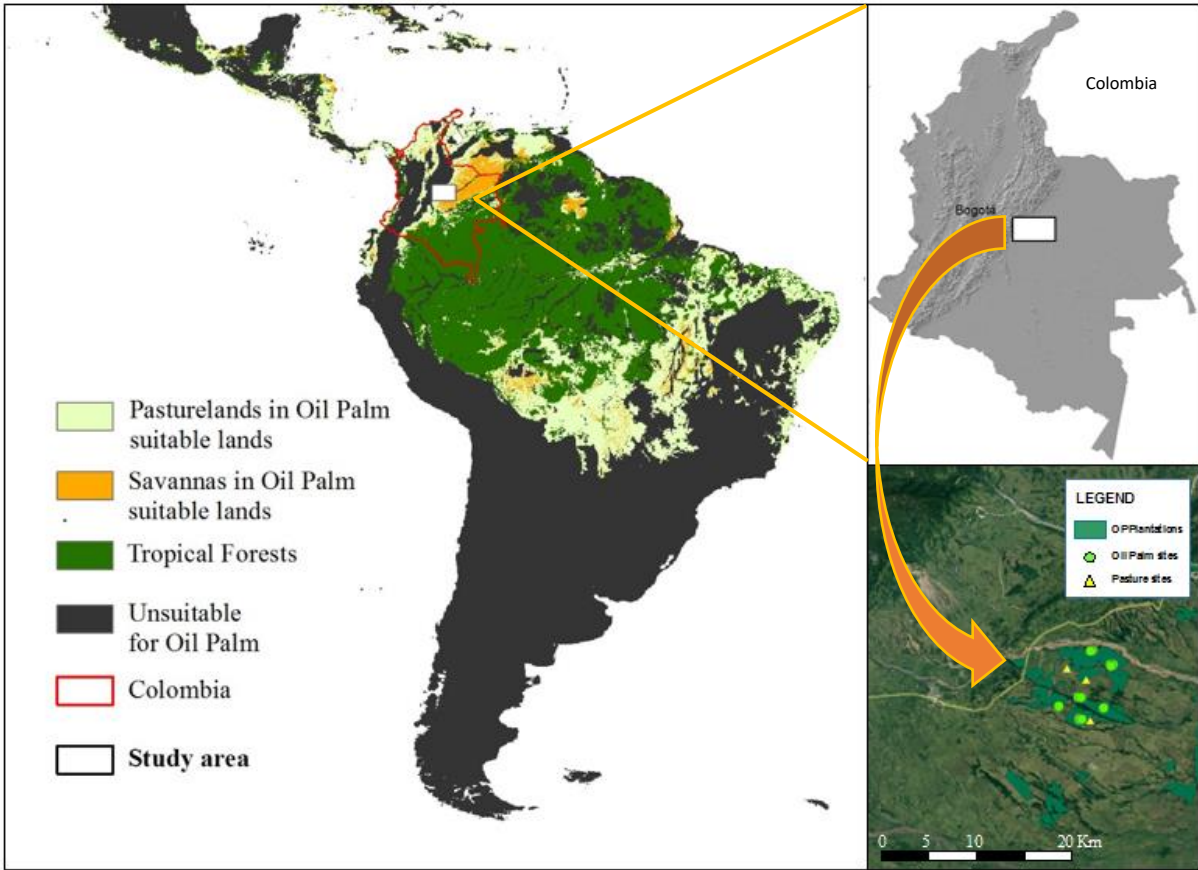
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Fig. S1. Map of study sites and the potential area for the expansion of OP in pasture lands in the Neotropics.

Table S1. Set of models tested for the bulk soil and pasture- and OP-derived carbon.

Table S2. Soil chemical, physical, and isotopic properties.



**Fig. S1. Map of study sites and the potential area for the expansion of OP in pasture lands in the Neotropics.**

**Table S1. Set of models tested for the bulk soil and pasture- and OP-derived carbon.**

| Soil layer                  | Model type                      | Function   | R2   | P value of model | P value of age | AIC   | k1 (yr-1) | e/x1/x2/A/c <sup>a</sup> | k2 (yr-1) | Slope 1 | Slope 2 |
|-----------------------------|---------------------------------|--|------|------------------|----------------|-------|-----------|--------------------------|-----------|---------|---------|
| Bulk soil; 0-50 cm          | Linear                          | F(t) = 99.64 - 0.78*t                                    | 0.66 | ***              | ***            | 126.5 | -         | -                        | -         | -       | -       |
| Bulk soil; 0-50 cm          | Segmented                       | F(t) = 105.71 - 1.26*t; F2(t) = 0.18*t; BP:36.1          | 0.73 | -                | ***            | 124.3 | -         | -                        | -         | ***     | NS      |
| Bulk soil; 0-50 cm          | Monoexponential                 | F(t) = 47.77 + (104.65-47.77)*exp(t*- (0.028))           | 0.73 | -                | -              | 125.8 | NS        | NS (0.0533)              | -         | -       | -       |
| Bulk soil; 0-50 cm          | Biexponential                   | No convergence   | -    | -                | -              | -     | -         | -                        | -         | -       | -       |
| Bulk soil; 0-50 cm          | Single exponential decay        | F(t) = 102.2*exp(t*- (0.010))                            | 0.71 | -                | -              | 124.9 | ***       | ***                      | -         | -       | -       |
| OP-derived C; 0-50 cm       | Linear                          | F(t) = 1.69 + 0.52*t                                     | 0.84 | ***              | ***            | 97.3  | -         | -                        | -         | -       | -       |
| Pasture-derived C; 0-50 cm  | Linear                          | F(t) = 93.6 - 1.19*t                                     | 0.80 | ***              | ***            | 129.2 | -         | -                        | -         | -       | -       |
| Pasture-derived C; 0-50 cm  | Monoexponential                 | F(t) = -32.59 + (396.96-(-32.59))*exp(t*- (0.013))       | 0.82 | -                | -              | 130.3 | NS        | NS                       | -         | -       | -       |
| Pasture-derived C; 0-50 cm  | Biexponential                   | No convergence   | -    | -                | -              | -     | -         | -                        | -         | -       | -       |
| Pasture-derived C; 0-50 cm  | Single exponential decay        | F(t) = 98.1 * exp(t*- (0.020))                           | 0.82 | -                | -              | 128.6 | ***       | ***                      | -         | -       | -       |
| Bulk soil; 0-10 cm          | Linear                          | F(t) = 28.9 - 0.19*t                                     | 0.40 | **               | **             | 97.2  | -         | -                        | -         | -       | -       |
| Bulk soil; 0-10 cm          | Segmented                       | F(t) = 31.9 - 0.42*t.....                                | 0.69 | -                | ***            | 88.3  | -         | -                        | -         | ***     | NS      |
| Bulk soil; 0-10 cm          | Monoexponential                 | F(t) = 19.4 + (32.05-19.4)*exp(t*- (0.066))              | 0.63 | -                | -              | 92.7  | NS        | ***                      | -         | -       | -       |
| Bulk soil; 0-10 cm          | Biexponential                   | F(t) = 32 * exp (t*- (0.017) + 0.009 * exp(t- (-0.12)    | 0.74 | -                | -              | 88.8  | **        | ***/NS                   | NS        | -       | -       |
| OP-derived C; 0-10 cm       | Linear                          | F(t) = 2.15 + 0.25*t                                     | 0.84 | ***              | ***            | 74.2  | -         | -                        | -         | -       | -       |
| OP-derived C; 0-10 cm       | Exponential rise to equilibrium | F(t) = -0.62 * exp (-0.038 * t) + 0.62)/0.038            | 0.91 | -                | -              | 66.0  | **        | ***                      | -         | -       | -       |
| Pasture-derived C; 0-10 cm  | Linear                          | F(t) = 26.7 - 0.44*t                                     | 0.75 | ***              | ***            | 101.2 | -         | -                        | -         | -       | -       |
| Pasture-derived C; 0-10 cm  | Monoexponential                 | F(t) = 4.37 + (32.01-4.37)*exp(t*- (0.054))              | 0.92 | -                | -              | 85.4  | **        | NS (0.07)                | -         | -       | -       |
| Pasture-derived C; 0-10 cm  | Biexponential                   | F(t) = 31.95 * exp (t*- (0.042) + 0.008 * exp(t- (-0.10) | 0.93 | -                | -              | 85.8  | ***       | ***/NS                   | NS        | -       | -       |
| Pasture-derived C; 0-10 cm  | Single exponential decay        | F(t) = 31.4 * exp(t*- (0.037))                           | 0.91 | -                | -              | 86.2  | ***       | ***                      | -         | -       | -       |
| Bulk soil; 10-20 cm         | Linear                          | F(t) = 22.20 - 0.18*t                                    | 0.55 | ***              | ***            | 86.2  | -         | -                        | -         | -       | -       |
| Bulk soil; 10-20 cm         | Segmented                       | F(t) = 24.49 - 0.36*t.....                               | 0.79 | -                | ***            | 75.5  | -         | -                        | -         | ***     | NS      |
| Bulk soil; 10-20 cm         | Monoexponential                 | F(t) = 12.6 + (24.28-12.6)*exp(t*- (0.048))              | 0.71 | -                | -              | 82.4  | NS        | ***                      | -         | -       | -       |
| Bulk soil; 10-20 cm         | Biexponential                   | No convergence   | -    | -                | -              | -     | -         | -                        | -         | -       | -       |
| OP-derived C; 10-20 cm      | Linear                          | F(t) = -0.27 + 0.10*t                                    | 0.84 | ***              | ***            | 46.4  | -         | -                        | -         | -       | -       |
| Pasture-derived C; 10-20 cm | Linear                          | F(t) = 22.5 - 0.28*t                                     | 0.77 | ***              | ***            | 85.4  | -         | -                        | -         | -       | -       |
| Pasture-derived C; 10-20 cm | Monoexponential                 | F(t) = 4.39 + (24.41-4.39)*exp(t*- (0.030))              | 0.85 | -                | -              | 82.2  | NS (0.08) | NS                       | -         | -       | -       |
| Pasture-derived C; 10-20 cm | Biexponential                   | No convergence   | -    | -                | -              | -     | -         | -                        | -         | -       | -       |
| Pasture-derived C; 10-20 cm | Single exponential decay        | F(t) = 24.1 * exp(t*- (0.02))                            | 0.84 | -                | -              | 80.7  | ***       | ***                      | -         | -       | -       |
| Bulk soil; 20-30 cm         | Linear                          | F(t) = 19.03 - 0.16*t                                    | 0.67 | ***              | ***            | 74.5  | -         | -                        | -         | -       | -       |
| Bulk soil; 20-30 cm         | Segmented                       | F(t) = 19.90 - 0.22*t.....                               | 0.69 | -                | **             | 75.1  | -         | -                        | -         | ***     | NS      |
| Bulk soil; 20-30 cm         | Monoexponential                 | F(t) = 3.96 + (19.56-3.96)*exp(t*- (0.021))              | 0.71 | -                | -              | 75.7  | NS        | NS                       | -         | -       | -       |
| Bulk soil; 20-30 cm         | Biexponential                   | No Convergence   | -    | -                | -              | -     | -         | -                        | -         | -       | -       |
| OP-derived C; 20-30 cm      | Linear                          | F(t) = -0.20 + 0.07*t                                    | 0.68 | ***              | ***            | 45.6  | -         | -                        | -         | -       | -       |
| Pasture-derived C; 20-30 cm | Linear                          | F(t) = 19.23 - 0.22*t                                    | 0.78 | ***              | ***            | 76.9  | -         | -                        | -         | -       | -       |
| Pasture-derived C; 20-30 cm | Monoexponential                 | F(t) = -41.47 + (19.42+41.47)*exp(t*- (0.048))           | 0.80 | -                | -              | 78.9  | NS        | NS                       | -         | -       | -       |
| Pasture-derived C; 20-30 cm | Biexponential                   | No convergence   | -    | -                | -              | -     | -         | -                        | -         | -       | -       |
| Pasture-derived C; 20-30 cm | Single exponential decay        | F(t) = 19.8 * exp(t*- (0.017))                           | 0.79 | -                | -              | 77.7  | ***       | ***                      | -         | -       | -       |
| Bulk soil; 30-50 cm         | Linear                          | F(t) = 29.42 - 0.25*t                                    | 0.69 | ***              | ***            | 87.7  | -         | -                        | -         | -       | -       |
| Bulk soil; 30-50 cm         | Segmented                       | F(t) = 27.7 - 0.04*t.....                                | 0.70 | -                | NS             | 89.1  | -         | -                        | -         | NS      | ***     |
| Bulk soil; 30-50 cm         | Monoexponential                 | No convergence   | -    | -                | -              | -     | -         | -                        | -         | -       | -       |
| Bulk soil; 30-50 cm         | Biexponential                   | No convergence   | -    | -                | -              | -     | -         | -                        | -         | -       | -       |
| OP-derived C; 30-50 cm      | Linear                          | F(t) = 0.02 + 0.10*t                                     | 0.57 | ***              | ***            | 66.4  | -         | -                        | -         | -       | -       |
| Pasture-derived C; 30-50 cm | Linear                          | F(t) = 29 - 0.35*t                                       | 0.73 | ***              | ***            | 95.9  | -         | -                        | -         | -       | -       |
| Pasture-derived C; 30-50 cm | Monoexponential                 | No convergence   | -    | -                | -              | -     | -         | -                        | -         | -       | -       |
| Pasture-derived C; 30-50 cm | Biexponential                   | No convergence   | -    | -                | -              | -     | -         | -                        | -         | -       | -       |
| Pasture-derived C; 30-50 cm | Single exponential decay        | F(t) = 29.75 * exp(t*- (0.017))                          | 0.69 | -                | -              | 99.0  | ***       | ***                      | -         | -       | -       |

<sup>a</sup>e= in Monoexponential function SOC stocks at equilibrium; x1= in Biexponential function SOC stocks of labile pool; x2= in Biexponential function SOC stocks of stable pool; A = in Exponential rise to equilibrium function is OP annual input; c = in single exponential decay function is the initial SOC stocks of pastures.

**Table S2. Soil chemical, physical, and isotopic properties.**

| Depth (cm)  | BD                 | Ca                  | K               | Mg             | Na            | P              | Sum cations            | EA           | ECEC         | BS             | pH           | 13C          | 15N         | CN          |
|-------------|--------------------|---------------------|-----------------|----------------|---------------|----------------|------------------------|--------------|--------------|----------------|--------------|--------------|-------------|-------------|
|             | Mg m <sup>-3</sup> | mg kg <sup>-1</sup> |                 |                |               |                | meq 100g <sup>-1</sup> |              |              | %              |              | ‰            |             |             |
| Pasture     |                    |                     |                 |                |               |                |                        |              |              |                |              |              |             |             |
| 0-10        | 1.27 (±0.06)       | 21.83 (±14.12)      | 50.73 (±20.56)  | 10.44 (±5.27)  | 9.35 (±4.80)  | 1.94 (±1.36)   | 0.37 (±0.18)           | 3.24 (±0.31) | 3.60 (±0.23) | 10.20 (±4.78)  | 4.49 (±0.32) | -17.2 (±1.8) | 5.3 (±0.8)  | 12.3 (±0.6) |
| 10-20       | 1.34               | 10.74 (±3.79)       | 22.49 (±4.34)   | 4.76 (±0.76)   | 6.64 (±1.32)  | 1.90 (±1.86)   | 0.18 (±0.03)           | 3.37 (±0.06) | 3.55 (±0.10) | 5.04 (±0.75)   | 4.42 (±0.12) | -15.8 (±0.7) | 7.3 (±0.6)  | 12.8 (±0.5) |
| 20-30       | 1.32               | 3.07 (±3.08)        | 15.41 (±2.11)   | 2.60 (±0.25)   | 4.99 (±1.45)  | 1.51 (±0.61)   | 0.10 (±0.02)           | 3.17 (±0.31) | 3.26 (±0.31) | 3.05 (±0.83)   | 4.59 (±0.14) | -14.3 (±0.4) | 8.7 (±0.6)  | 13.7 (±0.5) |
| 30-50       | 1.30               | 1.68 (±1.94)        | 12.89 (±2.47)   | 1.81 (±0.22)   | 3.61 (±2.59)  | 2.93 (±1.24)   | 0.07 (±0.01)           | 2.83 (±0.40) | 2.88 (±0.41) | 2.51 (±0.09)   | 4.47 (±0.20) | -13.7 (±0.7) | 9.3 (±1.1)  | 13.3 (±0.5) |
| OP-12 years |                    |                     |                 |                |               |                |                        |              |              |                |              |              |             |             |
| 0-10        | 1.25               | 29.89               | 54.90           | 26.28          | 4.60          | 9.24           | 0.53                   | 3.86         | 4.39         | 12.06          | 4.04         | -18.8        | 6.1         | 12.4        |
| 10-20       | 1.24               | 5.25                | 34.02           | 10.20          | 6.05          | 2.76           | 0.22                   | 3.82         | 4.04         | 5.56           | 4.10         | -15.8        | 7.6         | 13.2        |
| 20-30       | 1.33               | 9.65                | 25.89           | 6.68           | 5.88          | 3.89           | 0.20                   | 3.59         | 3.78         | 5.18           | 4.20         | -15.4        | 8.6         | 13.5        |
| 30-50       | 1.40               | 6.97                | 21.11           | 4.22           | 6.47          | 10.07          | 0.15                   | 3.43         | 3.58         | 4.25           | 4.22         | -16.3        | 9.3         | 12.1        |
| OP-18 years |                    |                     |                 |                |               |                |                        |              |              |                |              |              |             |             |
| 0-10        | 1.24 (±0.04)       | 87.12 (±48.09)      | 126.50 (±63.71) | 20.21 (±7.75)  | 4.53 (±3.28)  | 29.98 (±15.48) | 0.95 (±0.39)           | 3.23 (±0.59) | 4.18 (±0.20) | 23.00 (±10.79) | 4.31 (±0.19) | -19.5 (±0.7) | 5.9 (±0.6)  | 13.6 (±0.3) |
| 10-20       | 1.24               | 34.21 (±24.74)      | 79.15 (±28.52)  | 9.48 (±2.27)   | 4.94 (±2.77)  | 9.25 (±7.15)   | 0.47 (±0.20)           | 3.26 (±0.47) | 3.73 (±0.31) | 12.95 (±6.30)  | 4.28 (±0.05) | -15.8 (±0.7) | 7.7 (±0.4)  | 15.3 (±0.1) |
| 20-30       | 1.33               | 20.89 (±15.47)      | 48.27 (±13.33)  | 7.64 (±2.01)   | 5.09 (±3.44)  | 6.58 (±2.90)   | 0.31 (±0.10)           | 3.16 (±0.64) | 3.48 (±0.57) | 9.40 (±4.45)   | 4.41 (±0.15) | -14.3 (±0.3) | 9.2 (±0.3)  | 15.9 (±0.0) |
| 30-50       | 1.40               | 11.86 (±0.90)       | 25.43 (±11.25)  | 6.44 (±2.61)   | 3.33 (±3.07)  | 13.37 (±2.58)  | 0.19 (±0.02)           | 2.81 (±0.35) | 3.00 (±0.35) | 6.43 (±0.93)   | 4.48 (±0.13) | -13.6 (±0.2) | 10.4 (±0.3) | 15.9 (±0.3) |
| OP-30 years |                    |                     |                 |                |               |                |                        |              |              |                |              |              |             |             |
| 0-10        | 1.45 (±0.11)       | 93.77 (±16.83)      | 26.78 (±3.08)   | 15.76 (±11.78) | 2.71 (±2.79)  | 14.96 (±1.03)  | 0.68 (±0.18)           | 2.22 (±0.12) | 2.90 (±0.06) | 23.40 (±5.65)  | 4.24 (±0.11) | -23.2 (±0.8) | 5.6 (±0.4)  | 12.0 (±0.1) |
| 10-20       | 1.38               | 29.82 (±14.55)      | 15.93 (±1.74)   | 4.13 (±2.08)   | 3.03 (±4.28)  | 3.76 (±0.92)   | 0.24 (±0.07)           | 2.48 (±0.15) | 2.72 (±0.21) | 8.64 (±1.74)   | 4.45 (±0.01) | -18.8 (±0.3) | 7.3 (±0.5)  | 13.1 (±0.3) |
| 20-30       | 1.47               | 14.84 (±11.08)      | 16.40 (±2.19)   | 3.23 (±2.36)   | 10.31 (±8.89) | 3.85 (±1.17)   | 0.17 (±0.14)           | 2.62 (±0.09) | 2.79 (±0.23) | 5.98 (±4.56)   | 4.51 (±0.02) | -16.2 (±0.4) | 8.6 (±0.4)  | 13.4 (±0.3) |
| 30-50       | 1.51               | 2.25 (±3.19)        | 11.44 (±1.99)   | 1.39 (±0.83)   | 1.43 (±2.09)  | 3.77 (±2.48)   | 0.06 (±0.01)           | 2.63 (±0.06) | 2.69 (±0.07) | 2.17 (±0.27)   | 4.45 (±0.04) | -15.6 (±0.4) | 9.1 (±0.2)  | 12.5 (±0.7) |
| OP-32 years |                    |                     |                 |                |               |                |                        |              |              |                |              |              |             |             |
| 0-10        | 1.43               | 93.25               | 79.96           | 36.00          | 2.78          | 20.66          | 0.98                   | 2.06         | 3.05         | 32.25          | 4.10         | -22.80       | 6.2         | 12.1        |
| 10-20       | 1.22               | 27.38               | 49.20           | 9.84           | 3.49          | 7.04           | 0.36                   | 2.37         | 2.73         | 13.17          | 4.19         | -18.50       | 7.5         | 12.8        |
| 20-30       | 1.34               | 13.84               | 42.13           | 5.78           | 3.69          | 9.28           | 0.24                   | 2.56         | 2.80         | 8.60           | 4.18         | -16.60       | 8.6         | 13.4        |
| 30-50       | 1.50               | 4.93                | 35.58           | 5.03           | 3.93          | 5.29           | 0.17                   | 2.56         | 2.74         | 6.39           | 4.18         | -15.70       | 9.1         | 12.1        |
| OP-45 years |                    |                     |                 |                |               |                |                        |              |              |                |              |              |             |             |
| 0-10        | 1.42 (±0.05)       | 152.55 (±96.30)     | 90.18 (±21.98)  | 30.49 (±8.49)  | 3.83 (±0.68)  | 16.43 (±3.49)  | 1.26 (±0.60)           | 2.25 (±0.21) | 3.52 (±0.44) | 35.00 (±11.96) | 4.30 (±0.17) | -23.5 (±0.2) | 6.2 (±0.2)  | 10.2 (±0.6) |
| 10-20       | 1.45               | 84.39 (±43.08)      | 57.59 (±11.59)  | 13.20 (±3.61)  | 2.72 (±2.31)  | 3.50 (±0.47)   | 0.69 (±0.26)           | 2.56 (±0.38) | 3.25 (±0.64) | 20.80 (±3.55)  | 4.33 (±0.17) | -18.4 (±0.4) | 7.2 (±0.2)  | 10.0 (±0.5) |
| 20-30       | 1.40               | 62.90 (±25.02)      | 59.85 (±6.27)   | 11.19 (±3.14)  | 3.86 (±3.18)  | 1.91 (±0.83)   | 0.58 (±0.15)           | 2.86 (±0.35) | 3.43 (±0.35) | 16.89 (±4.37)  | 4.33 (±0.15) | -15.8 (±0.4) | 8.1 (±0.2)  | 10.5 (±1.0) |
| 30-50       | 1.50               | 34.56 (±19.82)      | 50.72 (±12.12)  | 7.83 (±3.10)   | 4.48 (±3.80)  | 0.70 (±0.64)   | 0.39 (±0.14)           | 2.77 (±0.38) | 3.16 (±0.31) | 12.45 (±5.11)  | 4.46 (±0.27) | -15.1 (±0.3) | 8.2 (±0.2)  | 9.7 (±0.3)  |
| OP-56 years |                    |                     |                 |                |               |                |                        |              |              |                |              |              |             |             |
| 0-10        | 1.15 (±0.08)       | 151.57 (±39.77)     | 110.77 (±29.88) | 59.41 (±23.27) | 9.19 (±1.32)  | 14.35 (±8.07)  | 1.58 (±0.43)           | 3.66 (±0.27) | 5.24 (±0.64) | 29.73 (±4.73)  | 4.40 (±0.16) | -24.3 (±0.3) | 6.5 (±0.3)  | 9.9 (±0.3)  |
| 10-20       | 1.17               | 61.31 (±10.22)      | 66.82 (±17.89)  | 23.61 (±8.24)  | 5.67 (±3.02)  | 1.26 (±0.77)   | 0.70 (±0.15)           | 4.39 (±0.20) | 5.09 (±0.32) | 13.65 (±2.42)  | 4.34 (±0.15) | -20.4 (±0.6) | 7.1 (±0.1)  | 9.9 (±1.4)  |
| 20-30       | 1.32               | 37.18 (±8.00)       | 49.46 (±8.26)   | 17.47 (±5.26)  | 6.74 (±4.59)  | 0.25 (±0.25)   | 0.49 (±0.09)           | 4.20 (±0.50) | 4.69 (±0.57) | 10.35 (±1.08)  | 4.42 (±0.08) | -19.5 (±0.4) | 7.1 (±0.2)  | 8.6 (±2.0)  |
| 30-50       | 1.39               | 26.74 (±10.32)      | 36.51 (±10.03)  | 16.18 (±6.51)  | 6.24 (±4.38)  | 0.25 (±0.17)   | 0.39 (±0.11)           | 3.57 (±0.66) | 3.95 (±0.73) | 9.85 (±1.73)   | 4.54 (±0.16) | -20.8 (±0.2) | 6.6 (±0.2)  | 5.9 (±0.3)  |

EA: exchangeable acidity; ECEC: effective cation exchange capacity; BS; base saturation; pH: in water (1:2.5).

Mean values (n=3 for all sites, except for 30 years oil palm (OP-30 years) where n=2, standard deviation between brackets; where no SD appears, values correspond to a single measurement