# Warming reduces the cover, richness and evenness of lichen-dominated biocrusts but promotes moss growth: Insights from an eight-year experiment

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The following Supporting Information is available for this article: Figs S1&S2 and Tables S1–S5

**Table S1** Results of a general linear mixed model showing the effects of the treatments on biocrust cover until the most complex factor interaction with significant ($< 0.05$) P-value (highlighted in bold). IBC = Initial biocrust cover.

| Factors | *DF* | *F*-value | *P*-value |
|---|---|---|---|
| IBC | 1 | 319.3 | **<0.001** |
| Warming | 1 | 65.9 | **<0.001** |
| Rain exclusion | 1 | 0.1 | 0.817 |
| Year | 6 | 37.7 | **<0.001** |
| IBC × Warming | 1 | 5.6 | **0.019** |
| IBC × Rain exclusion | 1 | 0.3 | 0.559 |
| IBC × Year | 6 | 38.1 | **<0.001** |
| Warming × Rain exclusion | 1 | 0.3 | 0.570 |
| Warming × Year | 6 | 18.9 | **<0.001** |
| Rain exclusion × Year | 6 | 1.4 | 0.204 |

**Table S2** Results of general linear mixed models showing the effects of the treatments on biocrust attributes (richness, diversity and evenness) until the most complex factor interaction with significant (<0.05) P-value (highlighted in bold). IBC = Initial biocrust cover, WARM = cover, WARM = Warming and RE = Rainfall exclusion. Warming and RE = Rainfall exclusion.

| Factors | Richness | | | Diversity | | | Evenness | | |
|---|---|---|---|---|---|---|---|---|---|
| | *DF* | *F*-value | *P*-value | *DF* | *F*-value | *P*-value | *DF* | *F*-value | *P*-value |
| IBC | 1, 74 | 159.3 | **<0.001** | 1, 74 | 54.4 | **<0.001** | 1 | 13.1 | **<0.001** |
| WARM | 1, 74 | 0.6 | 0.438 | 1, 74 | 22.0 | **<0.001** | 1 | 2.6 | 0.111 |
| RE | 1, 74 | 2.0 | 0.163 | 1, 74 | 3.0 | 0.088 | 1 | 4.3 | **0.038** |
| Year | 2, 146 | 62.5 | **<0.001** | 2, 146 | 14.7 | **<0.001** | 2 | 1.5 | 0.225 |
| IBC × WARM | 1, 74 | 1.1 | 0.301 | 1, 74 | 0.0 | 0.848 | 1 | 5.9 | **0.016** |
| IBC × RE | 1, 74 | 3.3 | *0.073* | 1, 74 | 4.0 | **0.049** | 1 | 0.3 | 0.579 |
| IBC × Year | 2, 146 | 14.1 | **<0.001** | 2, 146 | 10.3 | **<0.001** | 2 | 0.7 | 0.525 |
| WARM × RE | 1, 74 | 0.0 | 0.919 | 1, 74 | 1.1 | 0.293 | 1 | 4.3 | **0.039** |
| WARM × Year | 2, 146 | 90.1 | **<0.001** | 2, 146 | 40.3 | **<0.001** | 2 | 0.0 | 0.978 |
| RE × Year | 2, 146 | 1.3 | 0.285 | 2, 146 | 0.3 | 0.721 | 2 | 1.0 | 0.388 |

**Table S3** Results of PERMANOVA models showing the effects of the treatments on biocrust composition until the most complex factor interaction with significant (<0.05) P-value (highlighted in bold). IBC = Initial biocrust cover, WARM = Warming and RE = Rainfall exclusion.

| Factors | Presence/absence | | | Relative abundance | | |
|---|---|---|---|---|---|---|
| | *DF* | Pseudo-*F* | *P*-value | *DF* | Pseudo-*F* | *P*-value |
| IBC | 1 | 56.5 | **<0.001** | 1 | 84.3 | **<0.001** |
| WARM | 1 | 12.3 | **<0.001** | 1 | 20.6 | **<0.001** |
| RE | 1 | 1.3 | 0.313 | 1 | 0.7 | 0.639 |
| Year | 2 | 8.3 | **<0.001** | 2 | 7.5 | **<0.001** |
| IBC × WARM | 1 | 1.8 | 0.150 | 1 | 2.0 | 0.096 |
| IBC × RE | 1 | 1.8 | 0.147 | 1 | 2.6 | **0.036** |
| IBC × Year | 2 | 3.3 | **0.003** | 2 | 7.1 | **<0.001** |
| WARM × RE | 1 | 3.0 | **0.035** | 1 | 3.2 | **0.010** |
| WARM × Year | 2 | 8.6 | **<0.001** | 2 | 12.0 | **<0.001** |
| RE × Year | 2 | 0.5 | 0.801 | 2 | 0.4 | 0.886 |

**Table S4** Results of PERMANOVA models showing the average values between/within groups of the Bray-Curtis similarity index. This index quantify the compositional similarities (species presence and relative abundances) between plots clustered in different factor levels. Values lower than 50 are highlighted in bold. IBC = Initial biocrust cover, WARM = Warming and RE = Rainfall exclusion.

## Presence/absence

| | IBC × YEAR | | | | | WARM × YEAR | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | LIBC | HIBC | 2008 | 2011 | 2016 | - WARM | + WARM | 2008 | 2011 | 2016 |
| Between/within | Between LIBC | | Within LIBC | | | Between - WARM | | Within -WARM | | |
| 2008 | 53.93 | **48.41** | 53.93 | 56.54 | **49.57** | 55.53 | 57.41 | 55.53 | 58.82 | 58.04 |
| 2011 | 61.58 | 56.78 | 56.54 | 61.58 | 55.44 | 63.84 | 60.03 | 58.82 | 63.85 | 63.52 |
| 2016 | 54.09 | 54.66 | **49.57** | 55.44 | 54.09 | 69.99 | 50.85 | 58.04 | 63.52 | 69.99 |
| | Between HIBC | | Within HIBC | | | Between + WARM | | Within + WARM | | |
| 2008 | **48.41** | 78.83 | 78.83 | 71.00 | 65.59 | 57.41 | 58.76 | 58.76 | 56.68 | **49.51** |
| 2011 | 56.78 | 67.24 | 71.00 | 67.24 | 62.75 | 60.03 | 58.30 | 56.68 | 58.30 | 52.81 |
| 2016 | 54.66 | 61.11 | 65.59 | 62.75 | 61.11 | 50.85 | 53.03 | **49.51** | 52.81 | 53.03 |

### WARM × RE

| | - WA | + WA | | - RE | + RE |
|---|---|---|---|---|---|
| Between | Within - RE | | Between | Within - WARM | |
| - WARM | 63.36 | 55.81 | - RE | 63.36 | 60.93 |
| + WARM | 55.81 | 53.36 | + RE | 60.93 | 59.21 |
| | Within + RE | | | Within + WARM | |
| - WARM | 59.21 | 56.20 | - RE | 54.15 | 53.36 |
| + WARM | 56.20 | 55.19 | + RE | 53.36 | 55.19 |

## Relative abundance

| | IBC × YEAR | | | | | WARM × YEAR | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | LIBC | HIBC | 2008 | 2011 | 2016 | - WARM | + WARM | 2008 | 2011 | 2016 |
| Between/within | Between LIBC | | Within LIBC | | | Between - WARM | | Within -WARM | | |
| 2008 | 67.17 | 51.41 | 67.17 | 67.26 | 59.90 | 60.35 | 61.52 | 60.35 | 62.41 | 60.72 |
| 2011 | 69.63 | 59.86 | 67.26 | 69.63 | 63.43 | 65.76 | 63.61 | 62.41 | 62.41 | 60.72 |
| 2016 | 61.03 | 58.67 | 59.90 | 63.43 | 61.03 | 69.98 | 54.46 | 60.72 | 60.72 | 69.98 |
| | Between HIBC | | Within HIBC | | | Between + WARM | | Within + WARM | | |
| 2008 | 51.41 | 75.99 | 75.99 | 70.15 | 64.97 | 61.52 | 62.07 | 62.07 | 61.53 | 56.69 |
| 2011 | 59.86 | 67.71 | 70.15 | 67.71 | 64.36 | 63.61 | 63.88 | 61.53 | 63.88 | 61.30 |
| 2016 | 58.67 | 63.13 | 64.97 | 64.36 | 63.13 | 54.46 | 62.82 | 56.69 | 61.30 | 62.82 |

### WARM × RE

| | - WA | + WA | | - RE | + RE |
|---|---|---|---|---|---|
| Between | Within - RE | | Between | Within - WARM | |
| - WARM | 64.60 | 59.72 | - RE | 64.60 | 63.48 |
| + WARM | 59.72 | 60.18 | + RE | 63.48 | 62.88 |
| | Within + RE | | | Within + WARM | |
| - WARM | 62.88 | 60.49 | - RE | 60.18 | 60.84 |
| + WARM | 60.49 | 61.55 | + RE | 60.84 | 61.55 |

Table S4 continuation

| | | | Relative abundance | | | |
|---|---|---|---|---|---|---|
| | | | **IBC × RE** | | | |
| | LIBC | HIBC | | | - RE | + RE |
| Between | Within - RE | | Between | | Within LIBC | |
| LIBC | 64.50 | 55.97 | - RE | | 64.50 | 64.30 |
| HIBC | 55.97 | 67.90 | + RE | | 64.30 | 64.18 |
| | Within + RE | | | | Within HIBC | |
| LIBC | 64.19 | 57.17 | - RE | | 67.90 | 67.14 |
| HIBC | 57.17 | 67.00 | + RE | | 67.14 | 67.00 |

**Table S5** Results from SIMPER analysis showing the contribution (in %) of lichen species and mosses to the Euclidean squared distance in species relative abundance and presence between the levels of the factors with significant interactions (detected in the PERMANOVA analyses). For each interaction, the list of species ends when the accumulated contribution exceeds the value of 50%. The table includes all species with an individual contribution >10%. The species highlighted in bold are those with the greatest contribution in each interaction, and those in red are the species following a dynamic in presence and/or abundance not consistent the expected result (i.e., regression of the variables in the initial high biocrust cover (IBC) plots, a negative effect of Warming (WARM) factor, and a synergistic negative effect of the Warming and Rain exclusion (RE) interaction). The level of significance is: * = $P < 0.05$; ** = $P < 0.01$; *** = $P < 0.001$.

| Species | Presence/absence | | | Relative abundance | | |
|---|---|---|---|---|---|---|
| | Contribution (%) | Low IBC*** | High IBC*** | Contribution (%) | Low IBC*** | High IBC*** |
| | **IBC × Year**, difference of values between 2016 and 2008 | | | | | |
| *Buellia Zoharyi* | 8.04 | 0.25 | -0.25 | 10.02 | 0.10 | -0.21 |
| *Collema* spp. | 8.34 | 0.15 | 0.00 | - | - | - |
| *Diploschistes diacapsis* | **10.87** | **0.38** | **-0.25** | **16.59** | **0.23** | **-0.15** |
| *Fulgensia* spp. | 8.79 | -0.05 | -0.38 | **15.98** | **0.07** | **-0.27** |
| *Psora decipiens* | 9.08 | 0.13 | -0.35 | **-** | **-** | **-** |
| *Squamarina lentigera* | - | - | - | 9.36 | 0.21 | -0.10 |
| *Toninia sedifolia* | **10.86** | **0.18** | **-0.18** | - | - | - |
| | Contribution (%) | Low IBC* | High IBC*** | Contribution (%) | Low IBC** | High IBC*** |
| | **IBC × Year**, difference of values between 2011 and 2008 | | | | | |
| *Acarospora nodulosa* | 8.67 | 0.00 | -0.30 | - | - | - |
| *Collema* spp. | 10.09 | -0.08 | -0.18 | 9.17 | -0.02 | -0.05 |
| *Diploschistes diacapsis* | **13.51** | **0.23** | **-0.23** | **14.38** | **0.10** | **-0.11** |
| *Fulgensia* spp. | - | - | - | **12.29** | **0.04** | **-0.15** |
| *Psora decipiens* | **10.21** | **0.10** | **-0.15** | **-** | **-** | **-** |
| *Squamarina lentigera* | - | - | - | 10.01 | 0.15 | -0.06 |
| *Toninia sedifolia* | 10.21 | -0.08 | -0.30 | 9.31 | -0.04 | -0.15 |
| | Contribution (%) | Low IBC** | High IBC* | Contribution (%) | Low IBC*** | High IBC* |
| | **IBC × Year**, difference of values between 2016 and 2011 | | | | | |
| *Buellia Zoharyi* | **10.55** | **0.25** | **-0.03** | 11.37 | 0.10 | -0.06 |
| *Diploschistes diacapsis* | 9.71 | 0.15 | -0.03 | **11.51** | **0.13** | **-0.03** |
| *Fulgensia* spp. | 9.06 | -0.10 | -0.18 | **14.10** | **0.03** | **-0.12** |
| Mosses | <span style="color:red">9.86</span> | <span style="color:red">0.28</span> | <span style="color:red">0.15</span> | <span style="color:red">10.49</span> | <span style="color:red">0.10</span> | <span style="color:red">0.10</span> |
| *Psora decipiens* | 8.98 | 0.03 | -0.20 | 8.86 | 0.02 | -0.08 |
| *Toninia sedifolia* | <span style="color:red">**10.17**</span> | <span style="color:red">**0.25**</span> | <span style="color:red">**0.13**</span> | - | - | - |

**IBC × Year**, difference of values between high and low cover plots

| Species | Contribution (%) | 2008*** | 2016*** | Contribution (%) | 2008*** | 2016*** |
|---|---|---|---|---|---|---|
| *Buellia Zoharyi* | **16.50** | **0.88** | **0.38** | **25.22** | **0.49** | **-0.02** |
| *Diploschistes diacapsis* | **25.78** | **0.65** | **0.03** | 19.27 | 0.41 | -0.04 |
| *Fulgensia* spp. | - | - | - | 15.07 | 0.29 | -0.11 |
| *Psora decipiens* | 14.89 | 0.45 | -0.03 | - | - | - |
| *Squamarina lentigera* | 14.89 | 0.68 | 0.20 | **25.12** | **0.53** | **0.02** |

| Species | Contribution % | 2008*** | 2011*** | Contribution % | 2008*** | 2011*** |
|---|---|---|---|---|---|---|
| *Acarospora nodulosa* | 13.08 | 0.38 | 0.08 | - | - | - |
| *Buellia Zoharyi* | - | - | - | 11.51 | 0.49 | 0.34 |
| *Diploschistes diacapsis* | **29.43** | **0.65** | **0.20** | **23.54** | **0.41** | **0.20** |
| *Fulgensia* spp. | - | - | - | 19.18 | 0.29 | 0.10 |
| *Squamarina lentigera* | **17.80** | **0.68** | **0.33** | **21.54** | **0.53** | **0.33** |

| Species | Contribution % | 2011*** | 2016*** | Contribution % | 2011*** | 2016*** |
|---|---|---|---|---|---|---|
| *Buellia Zoharyi* | **24.25** | **0.65** | **0.38** | 34.02 | 0.34 | -0.02 |
| *Diploschistes diacapsis* | 9.82 | 0.20 | 0.03 | 14.22 | 0.20 | -0.04 |
| *Fulgensia* spp. | - | - | - | 10.71 | 0.10 | -0.11 |
| *Psora decipiens* | **16.23** | **0.20** | **-0.03** | - | - | - |
| *Squamarina lentigera* | - | - | - | **24.37** | **0.33** | **0.02** |

**IBC × RE**, difference of values between with and without RE

| Species | Contribution (%) | Low IBC- | High IBC* | Contribution (%) | Low IBC- | High IBC* |
|---|---|---|---|---|---|---|
| *Psora decipiens* | **69.60** | **0.17** | **-0.25** | **81.60** | **0.10** | **-0.13** |

**IBC × RE**, difference of values between high and low cover plots

| Species | Contribution (%) | Without RE*** | With RE*** | Contribution (%) | Without RE*** | With RE*** |
|---|---|---|---|---|---|---|
| *Psora decipiens* | **69.60** | **0.42** | **0.00** | **81=.60** | **0.20** | **-0.03** |

**WARM × Time**, difference of values between 2016 and 2008

| Species | Contribution (%) | Without WARM*** | With WARM*** | Contribution (%) | Without WARM*** | With WARM*** |
|---|---|---|---|---|---|---|
| *Collema* spp. | 8.70 | 0.28 | -0.13 | **-** | **-** | **-** |
| *Diploschistes diacapsis* | 9.14 | 0.28 | -0.15 | **16.23** | **0.23** | **-0.15** |
| *Fulgensia* spp. | **10.33** | **0.13** | **-0.5** | **17.11** | **0.11** | **-0.30** |
| *Toninia sedifolia* | **12.80** | **0.38** | **-0.38** | 9.15 | 0.12 | -0.17 |
| *Psora decipiens* | 9.22 | 0.18 | -0.40 | 8.79 | 0.09 | -0.19 |

**WARM × Time**, difference of values between 2011 and 2008

| Species | Contribution (%) | Without WARM* | With WARM** | Contribution (%) | Without WARM* | With WARM** |
|---|---|---|---|---|---|---|
| *Acarospora nodulosa* | 8.14 | -0.08 | -0.23 | **-** | **-** | **-** |
| *Diploschistes diacapsis* | **12.34** | **0.13** | **-0.13** | **14.24** | **0.08** | **-0.10** |
| *Fulgensia* spp. | - | - | - | **11.16** | **-0.01** | **-0.09** |
| *Collema* spp. | **11.34** | **0.05** | **-0.30** | 10.66 | 0.04 | -0.11 |
| *Toninia sedifolia* | 11.24 | 0.00 | -0.38 | 10.10 | -0.02 | -0.16 |

| Species | Contribution (%) | | | Contribution (%) | | |
|---|---|---|---|---|---|---|
| *Psora decipiens* | 10.36 | 0.10 | -0.15 | 9.44 | 0.05 | -0.09 |

**WARM × Time**, difference of values between 2016 and 2011

| Species | Contribution (%) | Without WARM[***] | With WARM[***] | Contribution (%) | Without WARM[***] | With WARM[**] |
|---|---|---|---|---|---|---|
| *Buellia Zoharyi* | **10.73** | **0.33** | **-0.10** | **11.28** | **0.13** | **-0.08** |
| *Diploschistes diacapsis* | 9.17 | 0.15 | -0.03 | 11.22 | 0.15 | -0.05 |
| *Fulgensia* spp. | **10.91** | **0.15** | **-0.43** | 16.53 | 0.12 | -0.21 |
| Mosses | <span style="color:red">9.24</span> | <span style="color:red">0.18</span> | <span style="color:red">0.25</span> | <span style="color:red">9.85</span> | <span style="color:red">0.09</span> | <span style="color:red">0.11</span> |
| *Psora decipiens* | - | - | - | 8.72 | 0.04 | -0.10 |
| *Toninia sedifolia* | 10.51 | 0.38 | 0.00 | - | - | - |

**WARM × Time**, difference of values between with and without WARM

| Species | Contribution (%) | 2008[-] | 2016[***] | Contribution (%) | 2008[-] | 2016[***] |
|---|---|---|---|---|---|---|
| *Diploschistes diacapsis* | - | - | - | **21.29** | **0.00** | **-0.37** |
| *Fulgensia* spp. | **19.00** | **0.00** | **-0.68** | **26.40** | **0.00** | **-0.42** |
| *Psora decipiens* | 13.79 | 0.10 | -0.48 | 12.70 | 0.06 | -0.22 |
| *Toninia sedifolia* | **23.46** | **0.20** | **-0.55** | 13.49 | 0.07 | -0.23 |

| Species | Contribution % | 2008[-] | 2011[*] | Contribution % | 2008[-] | 2011[**] |
|---|---|---|---|---|---|---|
| *Collema* spp. | **23.09** | **0.15** | **-0.20** | **19.06** | **0.06** | **-0.10** |
| *Diploschistes diacapsis* | 11.78 | 0.00 | -0.25 | **26.71** | **0.00** | **-0.18** |
| *Psora decipiens* | 11.78 | 0.10 | -0.15 | 14.41 | 0.06 | -0.07 |
| *Squamarina lentigera* | 16.96 | 0.13 | -0.18 | 10.03 | 0.01 | -0.10 |
| *Toninia sedifolia* | **26.50** | **0.20** | **-0.18** | 16.77 | 0.07 | -0.07 |

| Species | Contribution % | 2011[*] | 2016[***] | Contribution % | 2011[**] | 2016[***] |
|---|---|---|---|---|---|---|
| *Buellia Zoharyi* | **16.73** | **0.00** | **-0.43** | **14.75** | **0.01** | **-0.20** |
| *Diploschistes diacapsis* | - | - | - | 12.60 | -0.18 | -0.37 |
| *Fulgensia* spp. | **30.63** | **-0.10** | **-0.68** | 38.34 | -0.08 | -0.42 |
| *Toninia sedifolia* | 13.03 | -0.18 | -0.55 | - | - | - |

**WARM × RE**, difference of values between with and without RE

| Species | Contribution (%) | Without WARM[*] | With WARM[-] | Contribution (%) | Without WARM[*] | With WARM[-] |
|---|---|---|---|---|---|---|
| *Diploschistes diacapsis* | **15.80** | **0.13** | **-0.05** | **25.75** | **0.09** | **-0.03** |
| *Fulgensia* spp. | <span style="color:red">**57.57**</span> | <span style="color:red">**-0.18**</span> | <span style="color:red">**0.17**</span> | <span style="color:red">**65.62**</span> | <span style="color:red">**-0.10**</span> | <span style="color:red">**0.09**</span> |
| *Psora decipiens* | <span style="color:red">10.57</span> | <span style="color:red">-0.12</span> | <span style="color:red">0.03</span> | - | - | - |

**WARM × RE**, difference of values between with and without WARM

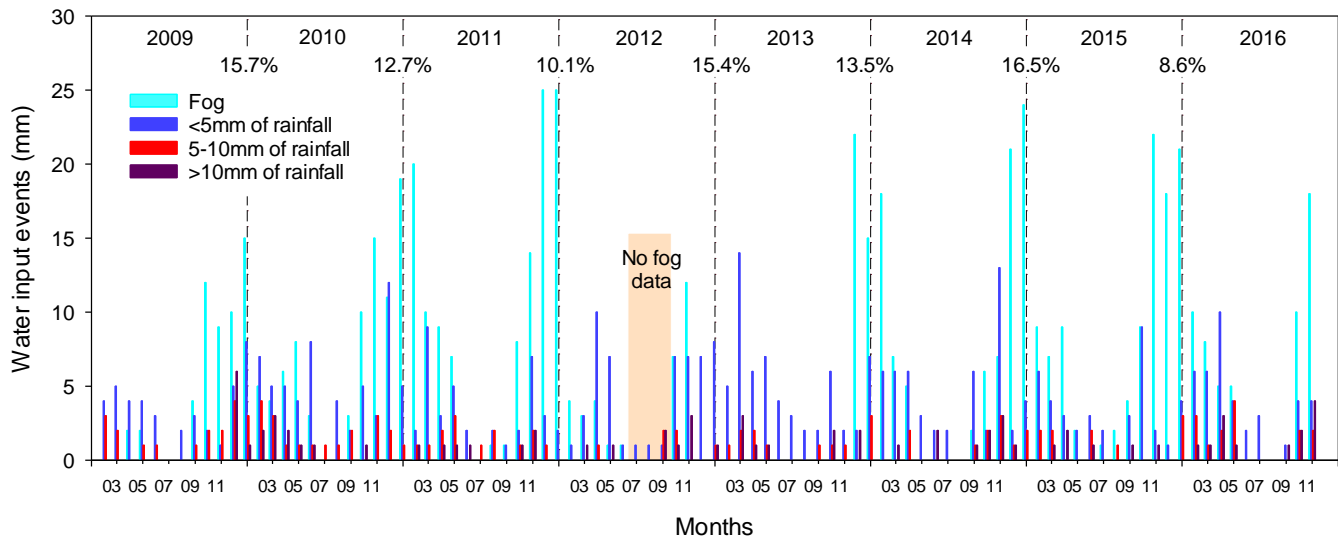| Species | Contribution (%) | Without RE[***] | With RE[**] | Contribution (%) | Without RE[***] | With RE[***] |
|---|---|---|---|---|---|---|
| *Diploschistes diacapsis* | **15.80** | **-0.13** | **-0.32** | **25.75** | **-0.12** | **-0.24** |
| *Fulgensia* spp. | <span style="color:red">**57.57**</span> | <span style="color:red">**-0.43**</span> | <span style="color:red">**-0.08**</span> | <span style="color:red">**65.62**</span> | <span style="color:red">**-0.26**</span> | <span style="color:red">**-0.07**</span> |
| *Psora decipiens* | <span style="color:red">10.57</span> | <span style="color:red">-0.25</span> | <span style="color:red">-0.10</span> | - | - | - |

**Fig. S1** Characterization of water input events throughout the experiment and average soil subsurface moisture (0–5 cm depth; percentages showed in the upper side of the figure) in control plots during lichens growth season (from November to March). An event was defined as the water input recorded or estimated on a daily basis. Fog was estimated using two criteria: 1) periods of relative air humidity (RH) higher than 97.5% (threshold established with the ± 2.5% accuracy error of the Hobo sensors used) and 2) separated at least 24 hours of a recorded rainfall event. As dense and prolonged fog events can be potentially recorded by the rain gauge, a rainfall event was defined as water pulses greater than 0.2 mm during 10 minutes or equal or greater than 0.4 mm during 20 minutes. However, the smallest water inputs (0.2 mm/day) not classified as fog because RH was lower than 97.5% were included in the category of < 5 mm of rainfall. When Hobo sensors were substituted by iButton sensors in the year 2013, RH was calculated with a correlation formula between these two brands (R2 = 0.99).
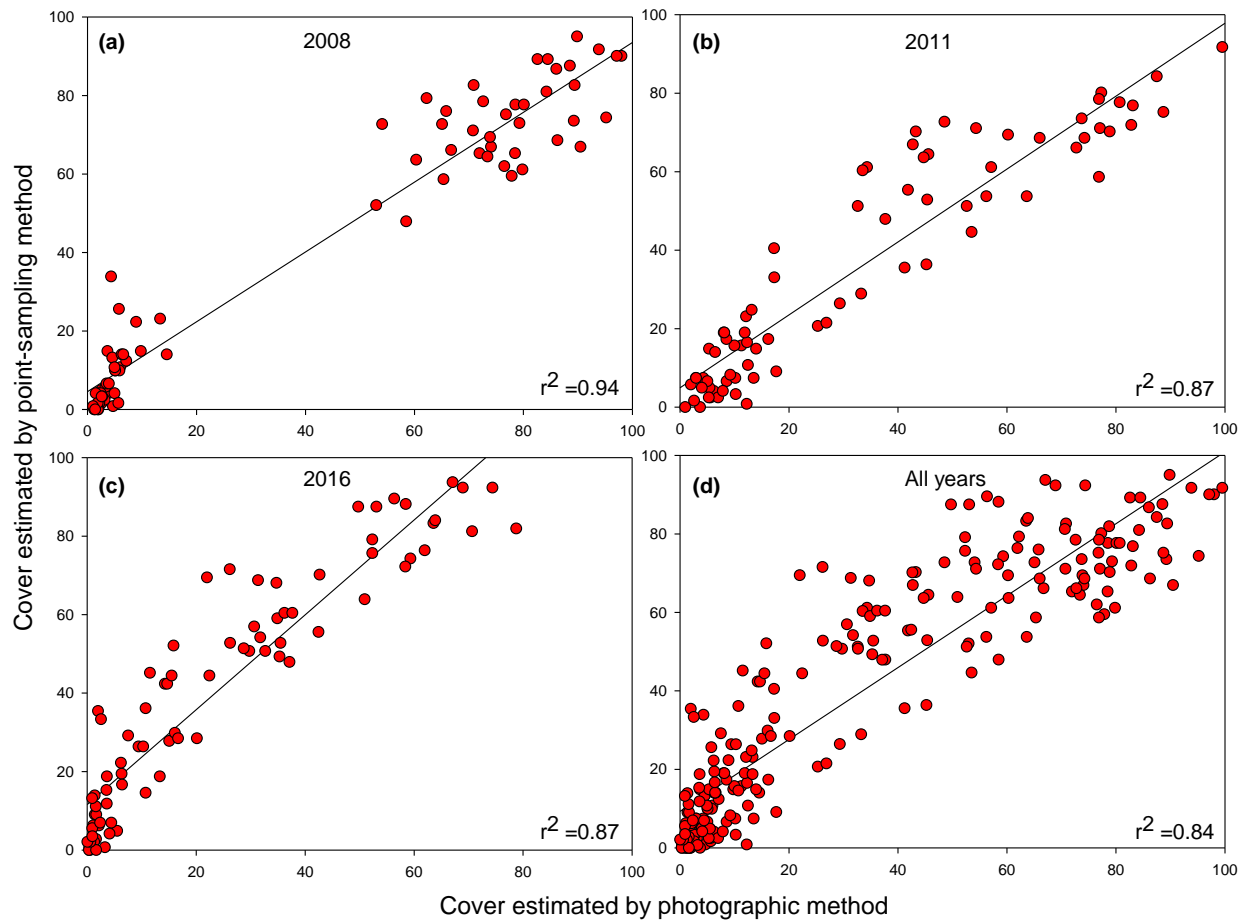
**Fig. S2** Relationship between the cover estimates obtained with the two methods used in the first (a), second (b) and third (c) sampling year, as well as with all the data pooled (d).