Master's thesis

NTNU
Norwegian University of Science and Technology
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Department of Biology

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Stochastic rain events increase NDVI through moss water content: a High-Arctic field experiment

Master's thesis in MLREAL
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Co-supervisors: Brage Bremset Hansen, Mathilde Le Moullec,
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Abstract

Measurements of Normalized Difference Vegetation Index (NDVI) through remote sensing is being used to indicate the productivity of the vegetation in the High Arctic, and how it is affected by climate changes. The interpretation of observed spatiotemporal variation and "greening" trends is often based on the assumption that they are mainly influenced by vascular plants, which typically are the focal functional group for large-scale studies of vegetation change. However, vegetated parts of the Arctic are to a large degree covered with a moss layer. Since NDVI values have been shown to increase rapidly with increasing moss water content, large-scale remotely sensed measurements may be strongly affected by moss cover and moist conditions. This may possibly affect the conclusions regarding processes occurring in vascular plants. In this study, measurements from three natural and two experimental rain events were combined to test for effects of moss water content on NDVI measurements, on the High-Arctic tundra of Svalbard (78°N), during the summer of 2018. Experimental rain events were induced by adding water (equivalent to 12 and 24 mm rain) to half of 24 plots (other plots were controls), in two vegetation types dominated by the mosses *Sanionia uncinata* and *Tomentypnum nitens*, respectively. There was a rapid change in moss water content as a result of natural and experimental rain events, and both events strongly affected moss water content and NDVI by increasing the values. Further, across plots and regardless of treatment and time of season, variation in moss water content was found to influence the NDVI values, and my analyses indicates that there was no strong long-term effect of rain events. This implies that the change in moss water content, due to stochastic rain events, may affect NDVI measurements over a short time (hours or a few days), but not necessarily over the season. Still, my result indicate that moss water content related to precipitation events can be affecting remote sensing data, such as peak or maximum NDVI values, when monitoring spatiotemporal variation in vegetation productivity in the Arctic. Hence, it should be considered as a potential source of noise and error.

Abstract in Norwegian

Målinger av ”Normalized Difference Vegetation Index” (NDVI) gjennom fjernmålinger blir brukt til å indikere produktiviteten til vegetasjonen i Høyarktis, og hvordan den påvirkes av klimaendringer. Tolkningen av observerte variasjoner i tid og rom, og ”grønnere” trender er ofte basert på antagelser om at de hovedsakelig er påvirket av vaskulære planter, som også typisk er den hovedfunksjonelle gruppen for storskala studier av vegetasjonsendring. Likevel er vegeterte deler av Arktis i stor grad dekket med et moselag. Siden NDVI-verdier har vist seg å øke raskt med økt vanninnhold i moser, betyr det at storskala fjernmålinger kan være sterkt påvirket av moselaget og fuktighetsforhold. Dette kan muligens påvirke konklusjoner angående prosesser som oppstår i vaskulære planter. I denne studien ble målinger fra tre naturlige og to eksperimentelle regnhendelser kombinert for å teste for effekten av vanninnholdet til moser på NDVI-målinger, på den Høyarktiske tundraen på Svalbard (78°N), i løpet av sommeren 2018. Eksperimentelle regnhendelser ble indusert ved å tilføre vann (tilsvarende 12 og 24 mm regn) på halvparten av 24 plot (resten var kontrollplot), i to vegetasjonstyper dominert av henholdsvis mosene *Sanionia uncinata* og *Tomentypnum nitens*. Det skjedde en rask endring i vanninnholdet til mosene som et resultat av naturlige og eksperimentelle regnhendelser, og begge regnhendelser påvirket vanninnholdet til mosene og NDVI sterkt ved å øke verdiene. Videre, på tvers av plot og uansett behandling og tid på sesongen, ble variasjon i vanninnholdet til mosene funnet å forklare NDVI-verdiene, og mine analyser indikerer at det ikke var noen sterk langtidseffekt av regnhendelsene. Dette betyr at en endring i vanninnhold til moser, som følge av stokastiske kraftige regnhendelser, kan påvirke NDVI-målinger over en kortere periode (timer eller få dager), men ikke nødvendigvis over sesongen. Likevel indikerer resultatene mine at vanninnholdet til moser relatert til regnhendelser kan påvirke fjernmålingsdata, slik som topp eller maksimum NDVI-verdier, når man overvåker variasjoner i vegetasjonsproduktivitet i tid og rom i Arktis. Derfor burde det bli vurdert som en potensielt betydelig feilkilde.

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1 Introduction

Future predictions suggest that effects of climate change will be strongest at high latitudes (IPCC, 2014). The Arctic already undergoes large changes in temperature, precipitation and ecosystem characteristics (AMAP, 2017) and it is warming twice as fast as lower latitudes (Overland et al., 2014). It is expected that a warmer and longer growing season will lead to an increase in primary production (Welker, Fahnestock and Jones, 2000; Lafleur and Humphreys, 2008). There is some evidence to suggest that greening is indeed occurring due to increasingly warmer summers (Elmendorf et al., 2012; Walker et al., 2012; Vickers et al., 2016), and that high latitude areas recently have experienced increased greenness (i.e. "Arctic greening") (Myneni et al., 1997; Jia et al., 2003; Walker et al., 2012; Xu et al., 2013; Park et al., 2016; Vickers et al., 2016). On the other hand, other studies suggest that the Arctic is instead undergoing a "browning" effect (Epstein et al., 2017), which may be due to rain-on-snow (ROS) events, lack of snow-cover, and outbreak of fungi and insects (Bokhorst et al., 2008; 2009; Bjerke et al., 2014; Phoenix and Bjerke, 2016).

Many of the studies reporting spatiotemporal variation or changes in productivity or biomass across large spatial or temporal scales, rely on remote sensing data such as the Normalized Difference Vegetation Index (NDVI). NDVI, developed by Rouse et al. (1974), is a cost-effective method used to study environmental changes (Kerr and Ostrovsky, 2003; Pettorelli et al., 2005). Several studies have shown that NDVI is correlated with primary production (Goward et al., 1985; Prince, 1991), vegetation biomass (Boelman et al., 2003; Goswami, 2015), leaf area index (LAI) (Tucker, 1979) and photosynthetically activity (Sellers, 1987; Myneni et al., 1995). Thus, the last decades, NDVI has been regarded as a valuable tool for measuring growth and changes in vegetation productivity at large spatial scales and across years (Braswell et al., 1997; Myneni et al., 1997; 2001). Nevertheless, though the correlation between NDVI and biomass is sturdy at large spatial scales, this relationship has shown to be less robust in plot-level studies (Hope, Kimball and Stow, 1993; Riedel et al., 2005).

The values of NDVI is calculated from the reflectance of near infrared and visible light from the vegetation. Green and dense vegetation absorbs a larger fraction of the visible light than sparse vegetation, which means that dense (green) vegetation reflects more near infrared light than sparse vegetation, and less visible light (Boelman et al., 2003). The Normalized Difference Vegetation Index is calculated as:

$$NDVI = \frac{(R_{NIR} - R_{RED})}{(R_{NIR} + R_{RED})} \tag{1}$$

R_{NIR} represents the reflectance of near infrared light (wavelength ~ 0.8 μm) and R_{RED} represents the visible red wavelength (wavelength ~ 0.6 μm) (Huete and Liu, 1994). NDVI is represented as a value between 0 and 1, whereas the value often situates around 0.05-0.7 (Tucker et al., 1986).

Spatiotemporal variation in large-scale NDVI is often interpreted in the context of vascular plants. However, there are still several assumptions related to the use and application of NDVI that must be tested and validated. In particular, the ground cover in high-latitude tundra vegetation is often dominated by mosses (Turetsky et al., 2012), hence NDVI measurements are often strongly affected by both vascular plants and bryophytes (mosses, lichens and liverworts) (Street et al., 2012; Karlsen et al., 2014; Yuan et al., 2014). Although mosses are not that often in focus in large-scale vegetation studies, nor that important for most herbivores, they are an important component in the ecosystem, contributing via productivity (Turetsky et al., 2010), carbon fluxes (Turetsky, 2003; Douma et al., 2007) and nutrient cycling (Turetsky, 2003; Nilsson and Wardle, 2005). Mosses are poikilohydric organisms, adjusting their water content from precipitation and surrounding water conditions (Proctor and Tuba, 2002; Oliver, Velten and Mishler, 2005). This means that when there is more water available, the moss will rapidly take up and contain more water, and vice versa. Moisture increases the short-term reflectance patterns of the vegetated surface, and this may potentially cause variation in NDVI unrelated to changes in vegetation (May et al., 2018). This implies that studies of spatiotemporal variation in NDVI, in moss-dominated areas, are likely affected by both stochastic variation in moisture level (i.e. mainly temporal variation), and moss cover and thickness (i.e. mainly spatial variation, but also temporal trends). Spatial variation in moss cover may therefore largely influence measurements of variation in NDVI in time and space, potentially confounding remote sensing studies used to measure spatiotemporal productivity of Arctic vegetation (Karlsen et al., 2014; May et al., 2018). In particular, these effects may be important when NDVI is used for assessing phenology over the season in vascular plants only, e.g. as a proxy of biomass availability for herbivores.

The main aim of this thesis is to combine data from experimental and natural rain events to test for the effect of moss water content on NDVI measurements, on the High-Arctic tundra on Svalbard. Here, vascular plant biomass is overall low and many areas are moss dominated (Elvebakk, 1994). NDVI measurements on Svalbard has previously been found to correlate well with annually production of "green" biomass by vascular plants, in a study site *not* strongly dominated by mosses (Karlsen et al., 2018). I expect that the temporal variation (i.e. on a daily scale) in NDVI of moss-dominated tundra is positively related to short-term variation in moss water content, driven by stochastic precipitation events. I therefore predict that experimentally induced rain events during summer increase NDVI in the short-term (i.e. daily scale). By analysing changes following natural rain events and comparing it with controls, I will also investigate whether the effects of experimental rain events are long-lasting through the summer.

2 Methods

2.1 Study area and study species

The study was conducted in Adventdalen, a valley close to Longyearbyen, Svalbard (78° 13'N, 15° 38'E). This High-Arctic climate has a mean annual temperature ranging from -12.6 °C in winter (i.e. December-February) to 5.0 °C in summer (i.e. June-August) (mean temperatures from 1957-2018), and the annual precipitation is low (mean = 196 mm, SD = 50 mm) (Norwegian Meteorological Institute, 1957-2018). The study site of this experiment was located in a flat and overall mesic area (Figure 1), and the vegetation in the area is dominated by the mosses *Sanionia uncinata* (Hedw.) Loeske and *Tomentypnum nitens* (Hedw.) Loeske (and to a less extent *Polyrichum, spp*.), the dwarf shrub *Salix polaris*, the herb *Bistorta vivipara* and the graminoids *Alopecurus borealis*, *Poa arctica* and *Luzula confusa* (Appendix, Table A1). The area is heavily grazed throughout the year by wild Svalbard reindeer (*Rangifer tarandus platyrhynchus*), and by barnacle geese (*Branta leucopsis*) and pink-footed geese (*Anser brachyrhynchus*) during spring and summer.

The focal species in this study are the two moss species *S. uncinata* (Figure 2A) and *T. nitens* (Figure 2B), hereafter referred to as *Sanionia* and *Tomentypnum*, respectively. *Sanionia* is a widespread moss, extending from the Arctic to the Antarctic (Hedenäs, 2003), and is one of the dominant moss species in the Arctic (Virtanen et al., 1997). It appears in a broad range of habitats (Hedenäs, 2003) ranging from wet to dry sites (Ueno, Imura and Kanda, 2001). *Tomentypnum* is a golden-brown moss typically growing in moist areas (Buck and Goffinet, 2000), spreading from the Arctic to the boreal zones (Buck and Goffinet, 2000; Porley, 2013). Both *Sanionia* and *Tomentypnum* are ectohydric mosses (Ochyra, Lewis and Bednarek-Ochyra, 2008; Zibulski et al., 2017). This means that they absorb and conduct water from precipitation through their surface, and do not have the same control over loss and gain of water content as vascular plants (Proctor, 2000).

2.2 Experimental design and natural rain events

The field experiment was conducted in Adventdalen, during July and August 2018. The experimental setup contained in total 24 plots (50 x 50 cm) in two vegetation types dominated by either of the two moss species *Sanionia* or *Tomentypnum* (Appendix, Table A1) (i.e. 12 plots per vegetation type). Measurements were done before and after three natural rain events during the course of the summer, and before and after two rounds of experimental water treatment (Figure 3). The experimental treatment was performed on half of the plots (i.e. watering plots), which were picked randomly, while the other half of the plots were kept as controls (Figure 1B). The water treatment consisted of pouring in total 3L (referred to as “Round 1”) and 6L (referred to as “Round 2”) of water progressively on the plots (three times with 1-2 hours between) (Figure 2 C-F), through holes in the watering can (simulating raindrops). Water was taken from a small stream nearby the study area. Given the plot size, 3L water equals 12 mm rain, and 6L water equals 24 mm rain, which reflects a “heavy” summer rain event according to meteorological records for the nearby weather station at Svalbard airport.

The natural rain events are referred to as “Event 1, 2, 3”. Event 1 (6.0 mm) occurred on 16th of July, Event 2 (3.6 mm) occurred on 20th of July, and Event 3 (19 mm) occurred just after the second round of experimental rain treatment, i.e. on 19th of August (Figure 3).

2.3 Measurements and data

Daily weather records are available from the manned weather station at Svalbard airport (eklima.met.no). NDVI was measured in all plots immediately before and after each natural/experimental rain event, with a hand-held Sky SpectroSense^{2+}. Sensors were placed in the middle of the plots, towards the sun, to avoid shadow while taking the measurements on a surface of 30 cm diameter. Soil moisture measurements were done by a HH2 Moisture Meter, before and after each natural/experimental rain event. Moisture was measured at five sites in the plots (within 50 x 50 cm), one in each corner and one in the middle. Furthermore, five samples (stems) from the respective moss species were sampled from all plots, before and after each natural/experimental rain event. Moss samples were collected with a tweezer and put in plastic tubes. The tubes were individually weighted before collection and filled with entire shoots of moss (not just the part that is over the ground but also the part that is under the ground), and the lid of the tubes was closed immediately to avoid loss of moisture. Afterwards, the tubes were brought back to the laboratory, weighted on a Mettler MT5 scale (wet weight), and put in the oven with open lid for drying in minimum overnight on 60°C. The lids of the tubes were closed right away after taking them out of the oven, and then the tubes were weighed again (dry weight). Water loss (moss wet weight - moss dry weight), moss dry weight and normalized water content were calculated afterwards.

Normalized water content (loss of water) was used as a measure of moss moisture, and was calculated as following:

$$\frac{Moss\ wet\ weight - Moss\ dry\ weight}{Moss\ dry\ weight} \tag{2}$$

The weight did not include the weight of the tubes. Normalized water content will hereafter be referred to as moss water content.

Present species in the different plots (Appendix, Table A1) was identified using the point intercept method (Levy and Madden, 1933). This was conducted in the period from 31st of July to 2nd of August 2018 (the peak of the growing season), using a 50 x 50 cm vegetation frame (in total 16 sub-squares) with a double layer of strings. The method involved lowering a pin vertically at each cross (created by the strings) and recording all the species the pin touched on the way down to the ground.

2.4 Statistical analyses

To test for the effect of moss water content on NDVI measurements, I used linear mixed-effect models within the package 'lme4' (Bates et al., 2019) in the statistical software R (version 3.4.1) (R Core Team, 2016). Plot effects were accounted for by setting 'Plot ID' (the individual plots) as a random intercept (random factor) in all models.

First, I calculated the change in NDVI, moss water content and soil moisture recorded before and after the natural/experimental rain events. I divided the analyses into natural and experimental rain and then again into the two different vegetation types (i.e. separate analyses for *Sanionia* and *Tomentypnum*). I then performed linear mixed effect models of change in NDVI, moss water content and soil moisture, focusing mainly on change in NDVI and moss water content. The following explanatory variables were used in my analyses (as factors): 'Treatment' (control plots or watering plots), 'Event' (the three different natural rain events), and 'Round' (the two different experimental rain events).

For natural rain events, 'Treatment' and 'Event' (see above) was set as explanatory variables. To investigate for a delayed effect of experimental rain events on the effect of natural rain events (especially for Round 2 and Event 3, which was close in time, see Figure 3), I tested for the interaction between 'Event' and 'Treatment' (Event:Treatment) as an explanatory variable. However, this was only statistically significant for change in soil moisture for *Tomentypnum*, and for the sake of simplicity this variable was excluded. Thus, I assumed that control plots and watering plots had the same effect of natural rain events. For model selection, I used the Akaike Information Criterion correction for small-sample bias (AICc), through the 'MuMIn' package (Barton, 2019) in R, due to the small sample size (Burnham and Anderson, 2002). Models were compared with parsimony, which means to use the fewest possible parameters to explain the most variance. To find the best fitted model, I used the rules for Δ_i ($AICc_i - AICc_{min}$): the model with a value below 0 are considered to have the best support from the data, and models with a value of 2 or less is perceived to have a sustainable support (Burnham and Anderson, 2002). Hence, the best fitted model was considered to be the one with the lowest AICc values. Models were fitted with restricted maximum likelihood (REML) to obtain parameter estimates (Bates, 2014). All possible subset models were tested for, included the null model, and I ended up with four optional models for each of the two vegetation types (Appendix, Table A2, Table A3). Similarly, for experimental rain events, 'Treatment' and 'Round' were included as explanatory variables. In the model selection I tested for all possible subset models, included the null model and the interaction between ‘Round’ and ‘Treatment’ (Round:Treatment), which gave five candidate models for each of the two vegetation types (Appendix, Table A4, Table A5).

To investigate more specific the effect of change in moss water content *per se* on change in NDVI, I did separate analyses including measured change in moss water content as predictor in the models. The analyses were divided in the same way as above, but control-plots were removed from the analysis related to experimental rain events (since they did not get any watering treatment, and no change in moss water content was expected). ‘Event’, ‘Treatment’ and ‘Change in moss water content’ was set as explanatory variables for natural rain events, and all possible subset models were tested for in the model selection, including the null model and the interaction between ‘Change in moss water content’ and ‘Event’ (Change in water content:Event). This gave eight optional models for each of the two vegetation types (Appendix, Table A6, Table A7). The models for experimental rain events contained ‘Round’ and ‘Change in water content’ as explanatory variables. All possible subset models were tested for, including the null model and the interaction between ‘Change in moss water content’ and ‘Round’ (Change in moss water content:Round). This resulted in four models for each of the two vegetation types (Appendix, Table A8, Table A9).

3 Results

3.1 Change in moss water content

The top-ranked model testing for the effect of natural rain events on change in moss water content, did only include ‘Event’ as an explanatory variable, which was the case for both vegetation types (Appendix, Table A2, Table A3). Natural rain proved to have an overall positive effect on moss water content (Figure 4 A-F). For *Sanionia*, natural rain had a positive stronger effect on change in moss water content in Event 1 than in Event 2, and Event 3 had a stronger effect than Event 2 (Table 1). Natural rain events had a positive effect on change in moss water content for *Tomentypnum* in Event 1, a smaller effect in Event 2, and a higher effect in Event 3 (Table 1). For experimental rain events, the top-ranked model for change in moss water content did only include ‘Treatment’ as an explanatory variable (Appendix, Table A4, Table A5). Experimental rain was found to have a positive effect on change in moss water content for watering plots in both *Sanionia* and *Tomentypnum* (Table 2, Figure 4 G-J).

3.2 Change in NDVI

The effect of natural rain events on change in NDVI was positive for both vegetation types (Figure 5 A-F). It gave a top-ranked model for *Sanionia* with intercept as the only explanatory variable (i.e. null model) (Appendix, Table A2), and ‘Event’ was set as the only explanatory variable for *Tomentypnum* (Appendix, Table A3). Natural rain had a positive effect on change in NDVI for *Tomentypnum* in Event 1, which was higher than the effect in Event 2, and smaller than the effect in Event 3 (Table 1). Experimental rain events were found to have a positive effect on change in NDVI for watering plots for both *Sanionia* and *Tomentypnum* (Table 2, Figure 5 G-J), with the top-ranked model only including ‘Treatment’ as an explanatory variable (Appendix, Table A4, Table A5).

3.3 Effect of changing moss water content on NDVI

When looking at the relationship between change in NDVI and change in moss water content *per se*, i.e. including ‘Change in moss water content’ as explanatory variable, I found that following natural rain, change in moss water content had a significant effect on change in NDVI in both *Sanionia* and *Tomentypnum* vegetation type (Table 3). The same trend was seen with experimental rain events (Table 4). Change in moss water content had a positive effect on change in NDVI for all events and rounds, except for Event 3 and Round 1 in *Tomentypnum* (Figure 6, A-D).

4 Discussion

In this field study, I investigated the effect of moss water content - linked with summer precipitation events - on NDVI values in the High Arctic. This was done by measuring plot-specific moss water content and NDVI before and after experimental and natural rain events. The results show, as expected, that both natural and experimental rain events affect the moss vegetation by increasing its water content (Table 1, Table 2, Figure 4 A-J). This caused a positive effect in NDVI after both natural and experimental rain events (Table 1, Table 2, Figure 5 A-J). Further, my results confirmed that it was the change in moss water content *per se* that had a positive effect on change in NDVI (Table 3, Table 4, Figure 6 A-D), which corresponds to my predictions.

Previous studies on moss have shown that NDVI values increase after watering the mosses (Douma et al., 2007; May et al., 2018) and that reflectance in Sphagnum species changes with changes in water content (Vogelmann and Moss, 1993). This is in contrast with a study made of Lovelock and Robinson (2002) which did not find a relationship between water content and NDVI. My results show a clear increase in NDVI values after both natural and experimental rain events (Table 1, Table 2, Figure 5 A-J), which is consistent with the majority of studies conducted. My study distinguishes from May et al. (2018) by doing the experiment in situ out in the field, and with natural rainfall. Douma et al. (2007) also did their measurements in the field, but this was only a small experiment which was not replicated. Furthermore, the advantage of this study is the capability to compare the measurements from natural rain events with experimental rain events, which confirmed the same trends. The results were largely consistent with expectations despite a limited sample size, indicating strong effects of water/precipitation on moss water content. Nevertheless, several experimental rain events could have been conducted to give a higher statistical power. The effect size for NDVI varied, with the highest increase around 0.06 (Table 1, Table 2). This is roughly an increase of 10% in NDVI, which is not a big change. May et al. (2018) had an increase of 0.06, and Douma et al. (2007) had an increase of 0.11 in NDVI from before to after watering. Although my changes are similar to May et al. (2018), this can not be compared directly due to the different type of studies. The scale of NDVI is narrow (0-1), which means that an increase of 0.06 will have a small impact. However, this effect depends on the natural variations such as background variation between the plots and between the rounds of controls. The year of 2018 did not have a particularly dry summer, which means that the effect would most likely have been greater if the moss had been dryer before natural/experimental rain (due to a lower starting point).

NDVI was higher in the plots treated with experimental rain events than in the control plots (Figure 5 A-J). This corresponds with the results of a study by Huemmrich et al. (2010), where NDVI (greenness) was higher in wet plots than in dry plots containing both vascular plants and moss, although they did not directly measure the water content of mosses. A reason for the greening effect may be because of the content of nutrients in the water. Mosses do not have roots like vascular plants and it has been suggested that they mainly get their nutrients from atmospheric deposition (Ayres et al., 2006). Even though Ayres et al. (2006) found that mosses also take up nitrogen from the soil, they will most likely get extra nutrient when water is added and through precipitation. This is particularly a possible effect in my study, since the experimental water was taken from a brook nearby the study area. A possible adjustment to this is to use distilled water, transported out in the field, which will not contain any nutrients.

For change in moss water content in natural rain events, Event 2 turned out to have the lowest effect for both vegetation types (Table 1). This may be explained by the fact that Event 2 contained the lowest amount of precipitation (Figure 3). I expected that Event 3 would have the highest effect on moss water content, since it was injected with the highest amount of water. This was the case for *Tomentypnum* but not for *Sanionia* (Table 1). A biological explanation for this may be that Event 3 happened a short time after Round 2 (Figure 3), and that *Sanionia* already may have been saturated with moisture. Nevertheless, the model selection suggested no strong interaction effect between 'Event' and 'Treatment'. For experimental rain events, I expected that change in moss water content in Round 2 would have a greater effect than Round 1 since it contained the double amount (Figure 3). The top-ranked model did however not include 'Round' as an explanatory variable (Appendix, Table A4, Table A5). Overall, all natural and experimental rain events had an increasing effect on moss water content. There was also found an effect of rain events on soil moisture (Appendix, Table A10, Table A11, Figure A1), which was expected. However, this effect was generally weak. This may come of the difficulty of penetrating the Moisture Meter through the moss layer and into the soil, particularly for *Tomentypnum*.

My results show that NDVI values are affected by moss water content (Table 3, Table 4, Figure 6 A-D). Due to their poikilohydric capability, mosses take up more water when there is more water available through the surrounding environment (Proctor and Tuba, 2002). When the mosses take up water it becomes greener (Figure 2 C-F), which will give higher NDVI values. I therefore expected that natural and experimental rain events containing a higher amount of water, would give a greater effect on NDVI values. However, the top-ranked models did not include ‘Round’ or ‘Event’ as explanatory variables (Appendix, Table A6-A9). For experimental rain event, the treatments and, thereby, measurements were done in different parts of the season, i.e. other factors may potentially have influenced the NDVI values. This implies that my result can not indicate if there was an increased effect of a higher amount of rain/water. To be able to compare the different rain events, the different levels of experimental rain amount should have been conducted on the same day, which would require a much larger sample size. For natural rain events for *Tomentypnum*, I found that the AICc-value for change in NDVI was higher for the top-ranked model including ‘Event’ as only explanatory variable (Appendix, Table A3), than for the top-ranked model including ‘Change in moss water content’ as only explanatory variable (Appendix, Table A7). The same trend is shown in *Sanionia* (Appendix, Table A1, Table A6). This means that for change in NDVI, the best explanatory model contains ‘Change in moss water content’ as the only explanatory variable. Thus, this may indicate that it is not only the amount of rain that affects the NDVI measurements, but also how much water the plot-specific moss layer can actually take up from the rain event, causing spatial variation in changes in NDVI. This implies that a small rain event is enough to potentially disturb NDVI measurements in the same way as a big rain event. It was not possible to compare these results directly in experimental rain events, due to different explanatory variables.

For experimental rain events, I waited approximately one hour after watering before taking the measurements. However, one could see the change in the colour of the vegetation quickly after the watering (Figure 2 C-F), which may be due to their ectohydric capability (Proctor, 2000). Zúñiga-González et al. (2016) found, in a study in Antarctica, that rehydration of *Sanionia* took less than 10 minutes. This indicates that moss water content may change fast and can cause large and rapid changes in NDVI, which corresponds to the findings in May et al. (2018). NDVI was not measured before the last natural rain event (the measurements from before Round 2 was used to compare with the after-values for both Round 2 and Event 3). If these measurements had been done, it would have been possible to see if the NDVI values decreased in-between Round 2 and Event 3 (Figure 3) and to see how long the effect is present. Nonetheless, my analyses indicate that there was no delayed effect of rain events on the plots. Therefore, my results suggests an effect of rain that may cause a difference in NDVI values over a short time (hours or days), but not over a longer period (seasonal).

Remote sensed data is used to study the effect of climate change on vegetation and productivity in the Arctic, and it is currently the most commonly used method (Raynolds et al., 2008; Walker et al., 2012). However, models using light reflectance consider the whole vegetation as one single unit (Huemmrrich et al., 2010), and on Svalbard, mosses contribute to a great part of the undercover vegetation (Elvebakk, 1994). An essential source of error when using NDVI in models to estimate green biomass may be variation in the water content (Shaver et al., 2007). My results show that measurements done with a handheld NDVI before and after natural and experimental rain events, for the same area, are different due to change in moss water content (Table 3, Table 4, Figure 6 A-D). This means that remotely-sensed NDVI values may also be affected. My results from a field experiment suggest that areas with moss as an important vegetation component, may have a major impact on measuring productivity and plant biomass with remote sensing, which corresponds to the lab study of May et al. (2018). Even small spatial variation in precipitation may possibly affect the values of NDVI measurements, which may be an explanation for why some areas show little spatial synchrony in remotely sensed terrestrial indices depended on synchrony of precipitation (Defriez and Reuman, 2017). Challenges with remote sensing is also found in aquatic environments, using satellite approaches for estimating chlorophyll a (greenness), where the methods have proven to have several uncertainties (Zimba and Gitelson, 2006; Serôdio et al., 2009; Lin et al., 2016).

In conclusion, my results strongly indicate that rapid changes in moss water content, due to stochastic rain events, may increase the NDVI values measured in moss-dominated tundra. This highlights the importance of considering the effects of precipitation and moss-dominant vegetation, when using remotely-sensed reflectance techniques to monitor the effects of climate change on the vegetation in the High Arctic, especially when the focus is on vascular plant vegetation. A future follow-up study may be to conduct several repeated NDVI and moss water content measurements after both natural and experimental rain events, to be able to investigate how long the “greening” effect is present. This will possibly provide a better overview over the long-term effect of precipitation on NDVI measurements.

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Kristine Valøen

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7 Tables

Table 1. Natural rain events model estimates (estimate ± SE) for models testing for the effect of natural rain events (explanatory variable) on change in moss water content/change in NDVI (response variables). The models are divided into the two vegetation types *Sanionia* (S) and *Tomentypnum* (T), and model estimates are based on the top-ranked linear mixed effect models. Intercept was removed for easier interpretation of the effect (size) of natural rain (because of the three factor levels).

Response variable	**Vegetation type**	**Event 1**	**Event 2**	**Event 3**
Change in moss water content (mg)	S	1.32 ± 0.16 (t=8.1)*^{a}	0.75 ± 0.16 (t=4.6)*^{ac}	1.28 ± 0.16 (t=7.9)*^{c}
	T	1.42 ± 0.08 (t=17.8)*^{ab}	0.80 ± 0.08 (t=10.0)*^{ac}	1.75 ± 0.08 (t=21.9)*^{bc}
Change in NDVI	S	0.038 ± 0.006 (t=5.9)*	0.038 ± 0.006 (t=5.9)*	0.038 ± 0.006 (t=5.9)*
	T	0.038 ± 0.003 (t=13.3)*^{ab}	0.021 ± 0.003 (t=7.3)*^{ac}	0.052 ± 0.003 (t=17.8)*^{bc}

* = statistically significance ($P < 0.05$) from 0
a = statistically significance ($P < 0.05$) between Event 1 and Event 2
b = statistically significance ($P < 0.05$) between Event 1 and Event 3
c = statistically significance ($P < 0.05$) between Event 2 and Event 3

Table 2. Experimental rain events model estimates (estimate ± SE) for models testing for the effect of treatment (i.e. plots treated with experimental rain), as explanatory variable, on change in moss water content/change in NDVI, as response variables. Intercept correlates to control plots. The models are divided into the two vegetation types *Sanionia* (S) and *Tomentypnum* (T), and model estimates are based on the top-ranked linear mixed effect models.

Response variable	**Vegetation type**	**Intercept (control plots)**	**Treatment**
Change in moss water content (mg)	S	-0.01 ± 0.09 (t=-0.1)	1.90 ± 0.12 (t=21.8)*
	T	-0.00 ± 0.07 (t=-0.0)	1.96 ± 0.09 (t=30.0)*
Change in NDVI	S	0.001 ± 0.007 (t=0.2)	0.059 ± 0.010 (t=8.4)*
	T	-0.001 ± 0.003 (t=-0.4)	0.053 ± 0.004 (t=17.1)*

* = statistically significance (P < 0.05) from 0

Table 3. Natural rain events model estimates (estimate ± SE) for models testing for the effect of change in moss water content (explanatory variable) on change in NDVI (response variable). The models are divided into the two vegetation types *Sanionia* (S) and *Tomentypnum* (T), and model estimates are based on the top-ranked linear mixed effect models.

Response variable	**Vegetation type**	**Intercept**	**Change in moss water content (mg)**
Change in NDVI	S	0.005 ± 0.009 (t=0.5)	0.029 ± 0.007 (t=4.3)*
	T	0.004 ± 0.005 (t=0.8)	0.025 ± 0.004 (t=6.9)*

* = statistically significance (P < 0.05) from 0

Table 4. Experimental rain events model estimates (estimate ± SE) for models testing for the effect of change in moss water content (explanatory variable) on change in NDVI (response variable). The models are divided into the two vegetation types *Sanionia* (S) and *Tomentypnum* (T), and model estimates are based on the top-ranked linear mixed effect models.

Response variable	**Vegetation type**	**Intercept**	**Change in moss water content (mg)**
Change in NDVI	S	-0.027 ± 0.031 (t=-0.9)	0.047 ± 0.016 (t=2.9)*
	T	-0.000 ± 0.003 (t=-0.1)	0.027 ± 0.002 (t=11.5)*

* = statistically significance ($P < 0.05$) from 0

8 Figures

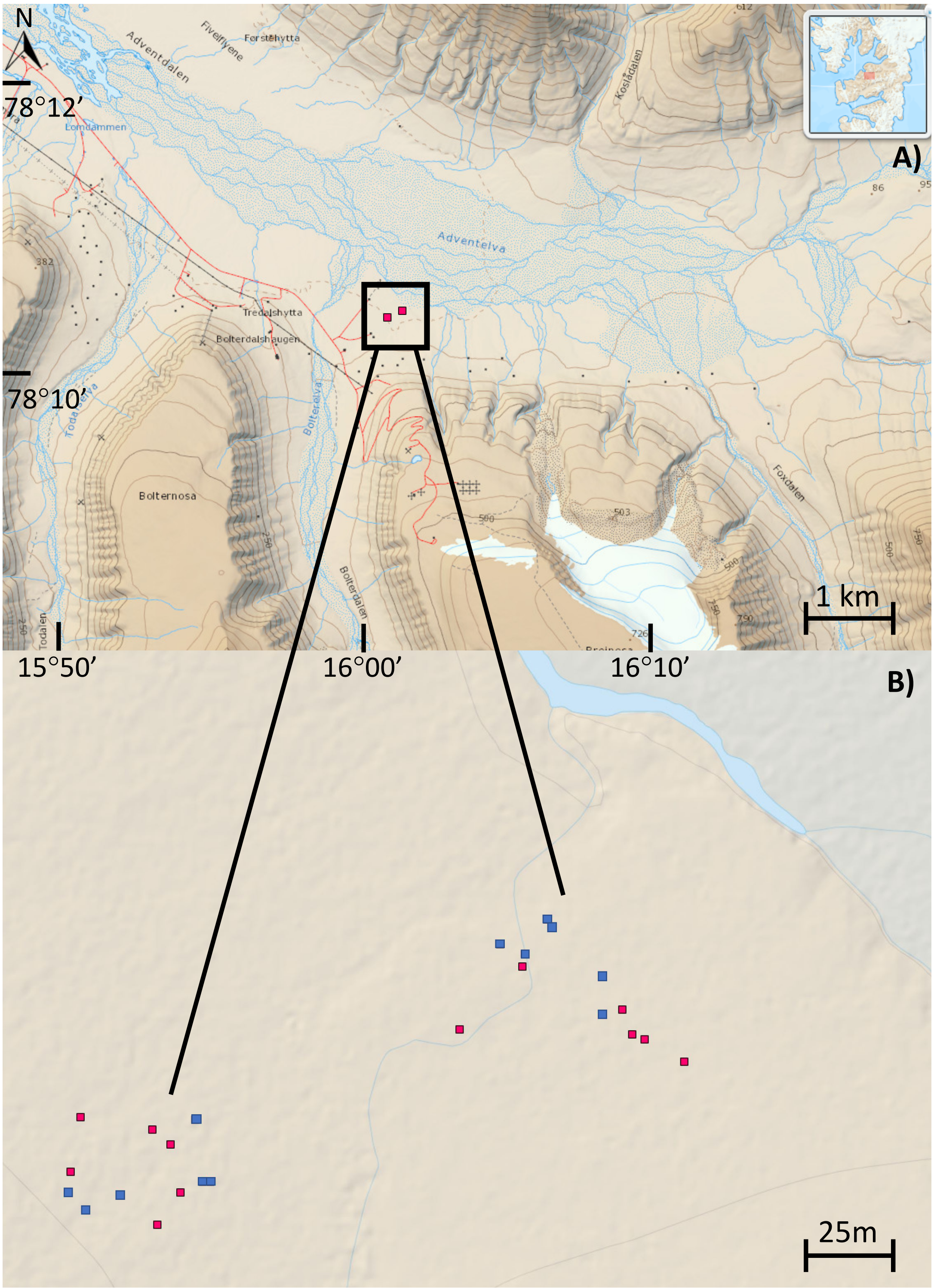

Figure 1. A) Map of the study area in Adventdalen. The two red spots indicate the location of the two different study sites for the two vegetation types. B) Map over the study area zoomed in, showing the different plots. The 12 spots to the right is the plots where the *Tomentypnum* vegetation is located, and the 12 spots to the left is the plots where *Sanionia* vegetation is located. Red spots indicate control plots, blue spots indicate treatment plots. Made by TopoSvalbard © Norwegian Polar Institute

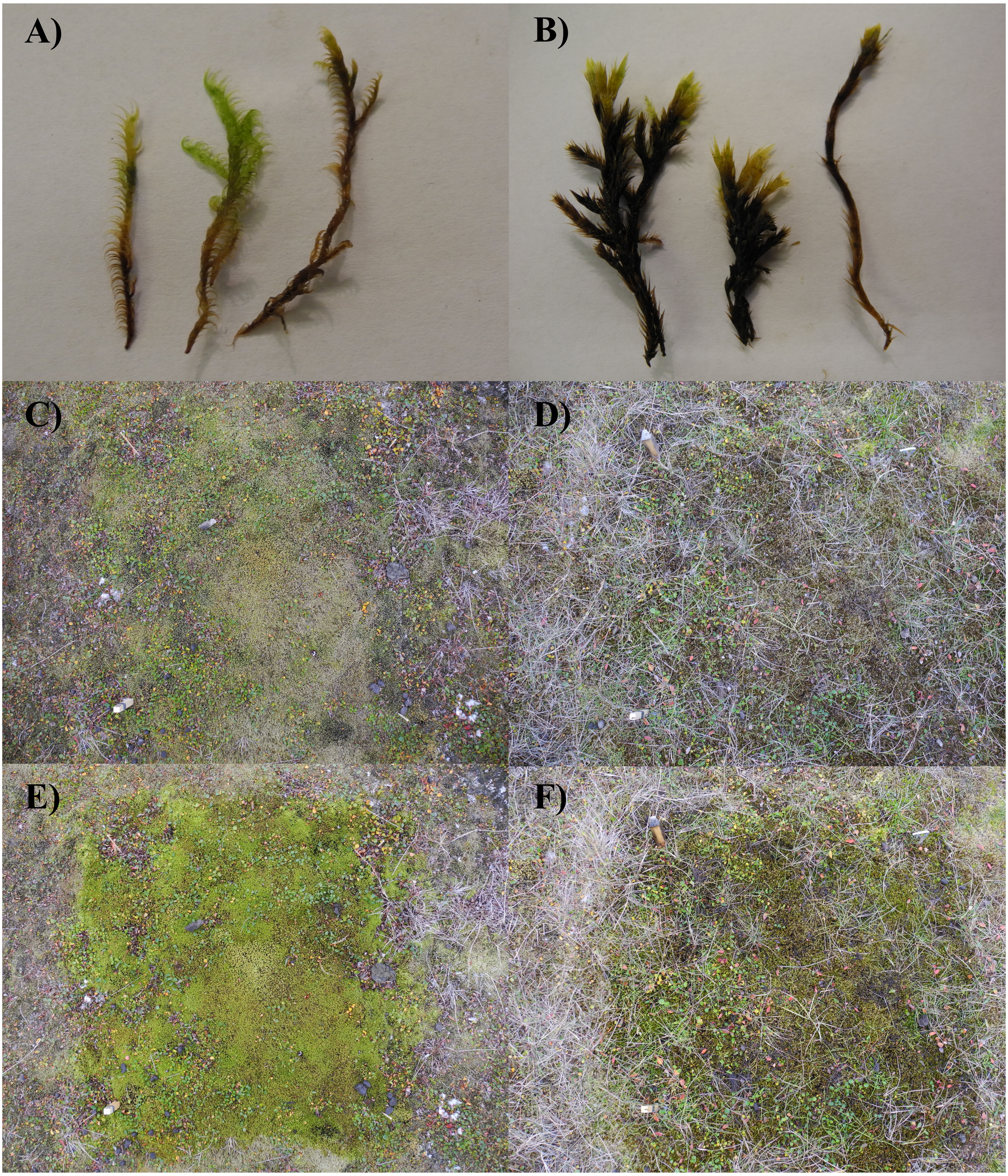

Figure 2. A) *Sanionia*. B) *Tomentypnum*. C) *Sanionia* plot before treated with experimental rain. D) *Tomentypnum* plot before treated with experimental rain. E) *Sanionia* plot after treated with experimental rain. F) *Tomentypnum* plot after treated with experimental rain. Photo: Kristine Valøen.

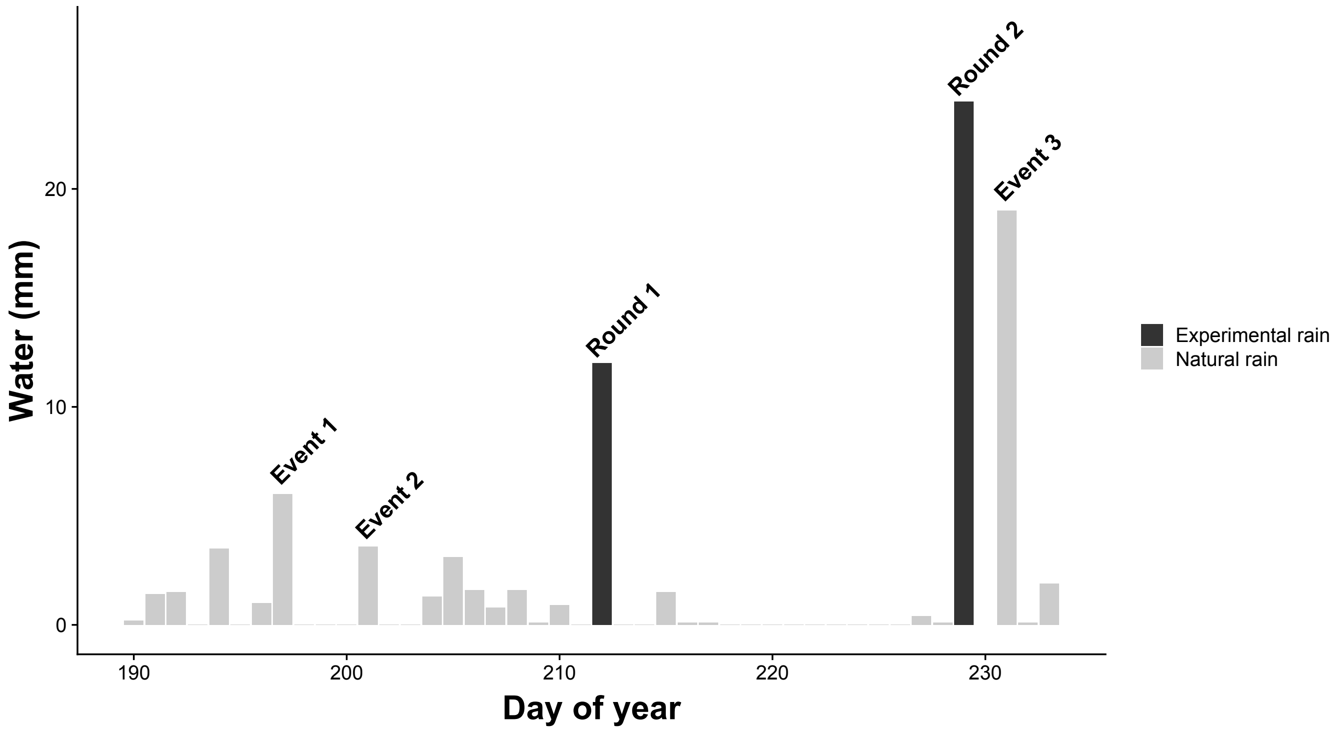

Figure 3. Timeline of the amount of precipitation (mm) and experimental rain (mm) during the summer of 2018. Grey bars represent the natural rain events, and black bars represent the experimental rain events. Natural rain events included in the study is marked with "Event", and experimental rain events are marked with "Round". The timeline starts at day 190 which corresponds to 9th of July.

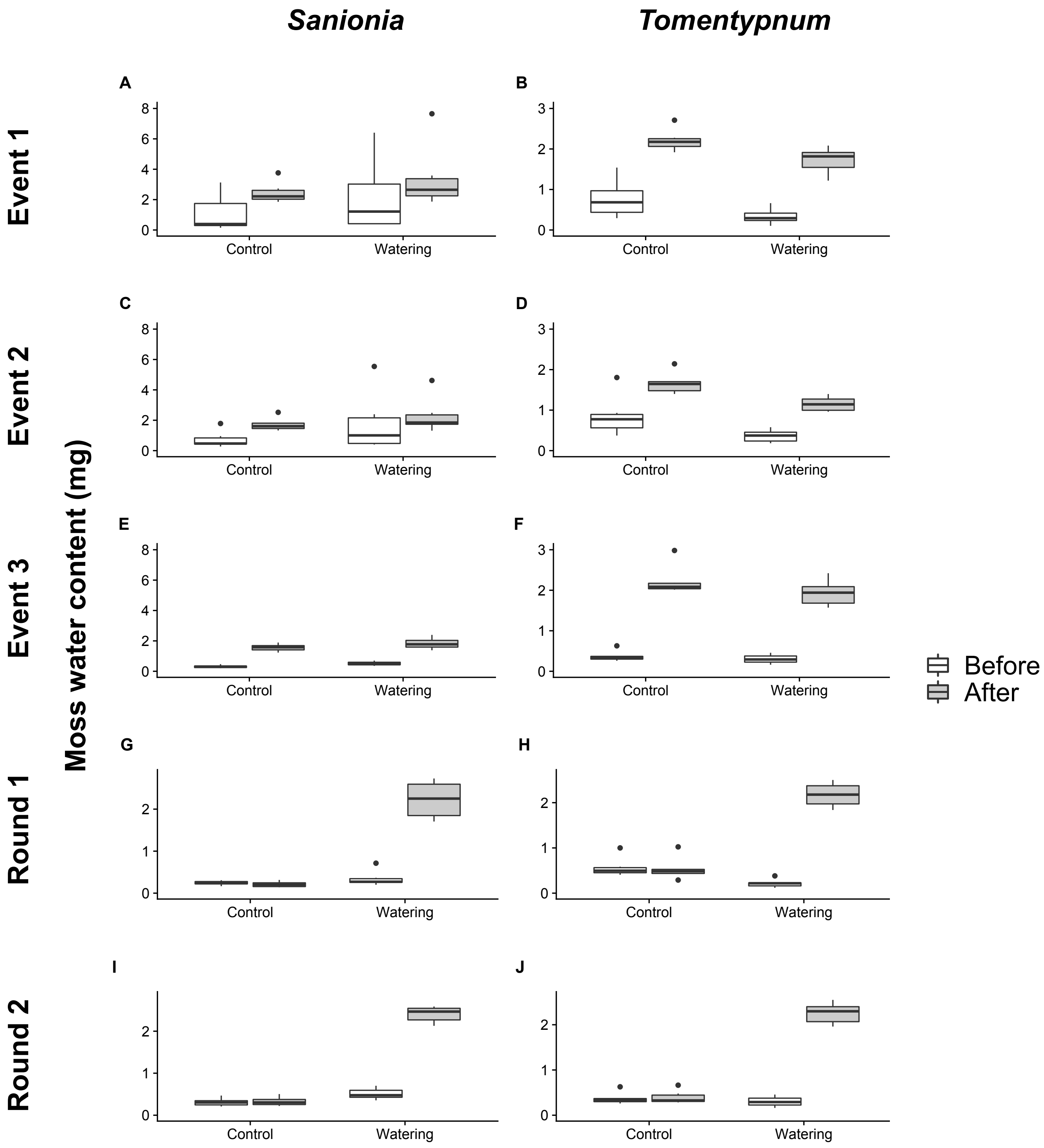

Figure 4. Moss water content (mg) for *Sanionia* (left) and *Tomentypnum* (right) before/after natural rain in Event 1 (A, B), Event 2 (C, D) and Event 3 (E, F), and before/after experimental rain in Round 1 (G, H) and Round 2 (I, J). White boxes indicate values before natural/experimental rain events, grey boxes indicate values after natural/experimental rain events.

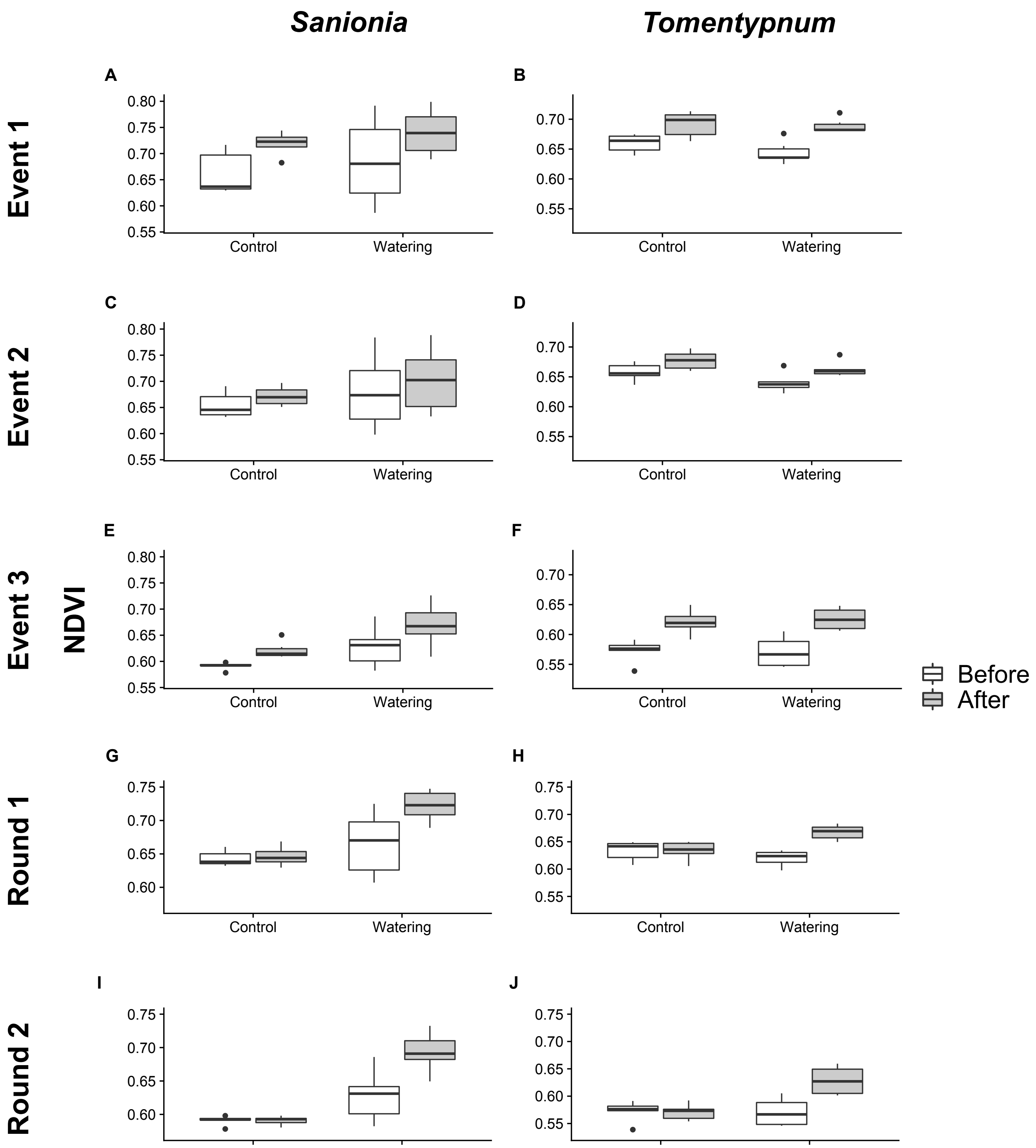

Figure 5. NDVI for *Sanionia* (left) and *Tomentypnum* (right) before/after natural rain in Event 1 (A, B), Event 2 (C, D) and Event 3 (E, F), and before/after experimental rain in Round 1 (G, H) and Round 2 (I, J). White boxes indicate values before natural/experimental rain events, grey boxes indicate values after natural/experimental rain events.

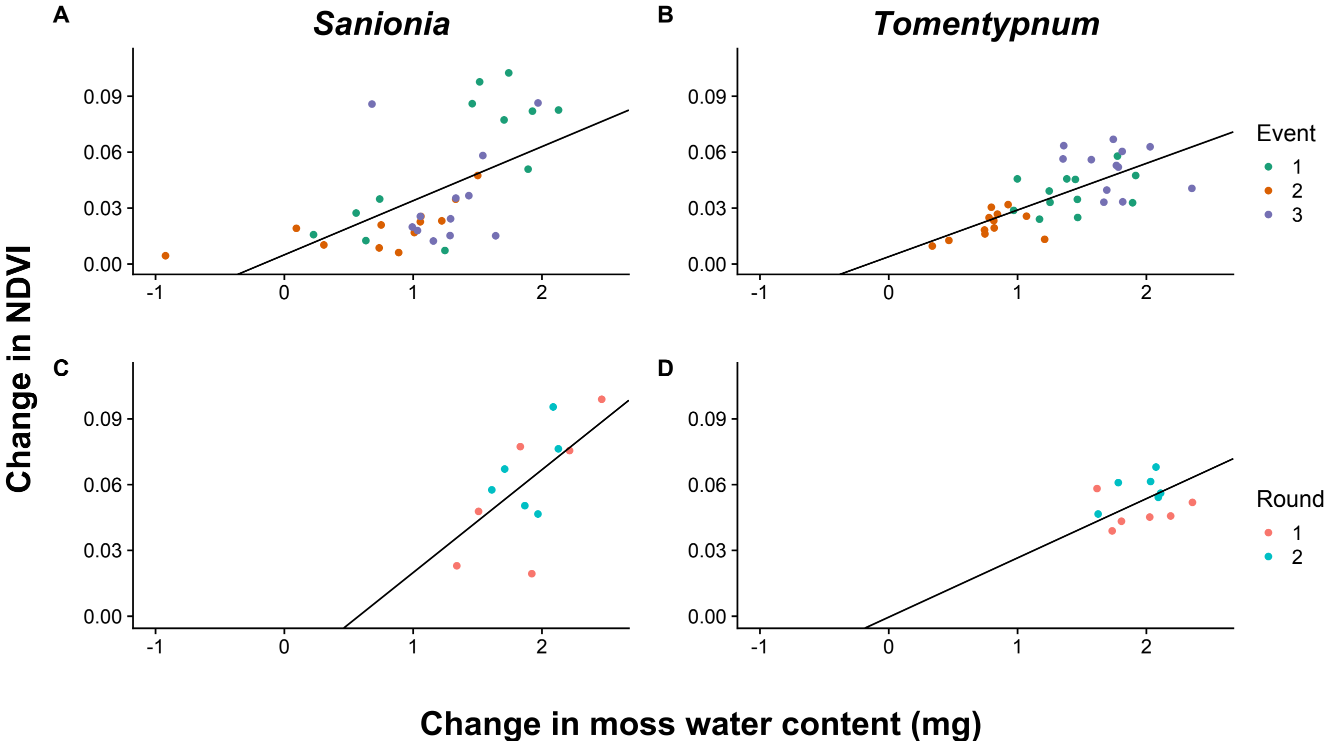

Figure 6. Change in NDVI as a function of change in moss water content (mg) for *Sanionia* (left) and *Tomentypnum* (right) in natural rain events (A, B), and in experimental rain events (C, D). Regression line are based on the top-ranked linear mixed effect model, with the following global model (always including Plot ID as random factor): change in NDVI ~ change in moss water content.

9 Appendix

Table A1. Overview of the different vegetation types found in the plots using point intercept method. Mean ± standard deviation is showed for both control and watering plots for the two vegetation types *Sanionia* (S) and *Tomentypnum* (T). Bolded cells show the dominance of *Sanionia* and *Tomentypnum* respective to their vegetation.

Species/group	**S (control)**	**S (watering)**	**T (control)**	**T (watering)**
Sanionia	**22.7 ± 1.5**	**21.7 ± 3.3**	2.7 ± 1.8	4.8 ± 3.1
Tomentypnum	0.2 ± 0.4	0.8 ± 2.0	**23.7 ± 0.5**	**19.7 ± 2.2**
Other moss	0.3 ± 0.8	0.6 ± 1.7	1.0 ± 1.6	1.2 ± 2.2
Graminoids	0.1 ± 0.3	0.3 ± 1.0	1.0 ± 1.7	0.9 ± 1.5
Dwarf shrub	8.5 ± 2.7	4.3 ± 1.6	4.5 ± 3.1	3.5 ± 2.1
Herb	0.2 ± 0.4	0.2 ± 0.4	0.8 ± 0.8	0.3 ± 0.5
Lichen	0.2 ± 0.4	0.5 ± 0.8	-	0.3 ± 0.8
Equisetum	-	1.8 ± 4.0	3.2 ± 2.9	2.8 ± 1.6

Table A2. Natural rain events model selection table showing the best model for *Sanionia*, using a linear mixed-effect model. Top-ranked model is marked with bold face. Global models (always including Plot ID as random factor):

Change in moss water content ~ Event + Treatment

Change in NDVI ~ Event + Treatment

Change in soil moisture ~ Event + Treatment

Parameter	Rank	Event	Treatment	AIC_c	ΔAIC_c
Change in moss water content	**1**	**+**		**69.7**	**0**
	2			72.0	2.3
	3	+	+	72.9	3.3
	4		+	74.9	5.3
Change in NDVI	**1**			**-138.7**	**0**
	2	+		-134.6	4.1
	3		+	-129.5	9.3
	4	+	+	-124.5	14.3
Change in soil moisture	**1**	**+**		**178.5**	**0**
	2	+	+	179.5	1.1
	3			195.5	17.0
	4		+	195.8	17.4

Table A3. Natural rain events model selection table showing the best model for *Tomentypnum*, using a linear mixed-effect model. Top-ranked model is marked with bold face. Global models (always including Plot ID as random factor):

Change in moss water content ~ Event + Treatment

Change in NDVI ~ Event + Treatment

Change in soil moisture ~ Event + Treatment

Parameter	Rank	Event	Treatment	AIC_c	ΔAIC_c
Change in moss water content	**1**	**+**		**27.7**	**0**
	2	+	+	32.4	4.7
	3			58.3	30.6
	4		+	62.3	34.6
Change in NDVI	**1**	**+**		**-193.9**	**0**
	2	+	+	-185.8	8.1
	3			-180.1	13.9
	4		+	-171.2	22.8
Change in soil moisture	**1**	**+**	**+**	**190.7**	**0**
	2	+		191.2	0.5
	3		+	200.8	10.1
	4			201.5	10.8

Table A4. Experimental rain events model selection table showing the best model for *Sanionia*, using a linear mixed-effect model. Top-ranked model is marked with bold face. Global models (always including Plot ID as random factor):

Change in moss water content ~ Round x Treatment

Change in NDVI ~ Round x Treatment

Change in soil moisture ~ Round x Treatment

Parameter	Rank	Round	Treatment	Round: Treatment	AIC_c	ΔAIC_c
Change in moss water content	**1**		**+**		**6.6**	**0**
	2	+	+		13.4	6.8
	3	+	+	+	19.3	12.7
	4				36.7	30.1
	5	+			43.1	36.5
Change in NDVI	**1**		**+**		**-108.5**	**0**
	2				-102.6	5.9
	3	+	+		-96.4	12.1
	4	+			-90.8	17.8
	5	+	+	+	-87.6	20.9
Change in soil moisture	**1**	**+**	**+**	**+**	**106.5**	**0**
	2	+	+		110.8	4.3
	3	+			116.9	10.4
	4		+		117.4	10.9
	5				123.3	16.9

Table A5. Experimental rain events model selection table showing the best model for *Tomentypnum*, using a linear mixed-effect model. Top-ranked model is marked with bold face. Global models (always including Plot ID as random factor):

Change in moss water content ~ Round x Treatment

Change in NDVI ~ Round x Treatment

Change in soil moisture ~ Round x Treatment

Parameter	**Rank**	**Round**	**Treatment**	**Round: Treatment**	**AIC_c**	**ΔAIC_c**
Change in moss water content	**1**		**+**		**-4.9**	**0**
	2	+	+		2.3	7.2
	3	+	+	+	8.4	13.3
	4				31.3	36.3
	5	+			38.2	43.2
Change in NDVI	**1**		**+**		**-128.7**	**0**
	2	+	+		-117.4	11.3
	3	+	+	+	-110.3	18.4
	4				-110.0	18.7
	5	+			-99.1	29.7
Change in soil moisture	**1**	**+**	**+**	**+**	**105.9**	**0**
	2	+	+		107.0	1.1
	3	+			118.5	12.6
	4		+		126.7	20.8
	5				137.9	32.0

Table A6. Natural rain events model selection table showing the best model for *Sanionia*, using a linear mixed-effect model. Top-ranked model is marked with bold face. Global models (always including Plot ID as random factor):

Change in NDVI ~ Change in moss water content x Event + Treatment

Parameter	Rank	Event	Treatment	Change in moss water content	Change in moss water content: Event	AIC_c	ΔAIC_c
Change in NDVI	**1**			**+**		**-141.4**	**0**
	2	+				-134.6	6.8
	3		+	+		-132.5	8.9
	4		+			-129.5	12.0
	5	+		+		-127.9	13.5
	6	+	+	+		-118.1	23.3
	7	+		+	+	-115.3	26.1
	8	+	+	+	+	-104.8	36.6

Table A7. Natural rain events model selection table showing the best model for *Tomentypnum*, using a linear mixed-effect model. Top-ranked model is marked with bold face. Global models (always including Plot ID as random factor):

Change in NDVI ~ Change in moss water content x Event + Treatment

Parameter	Rank	Event	Treatment	Change in moss water content	Change in moss water content: Event	AIC_c	ΔAIC_c
Change in NDVI	**1**			**+**		**-194.4**	**0**
	2	+				-193.9	0.4
	3		+	+		-188.4	5.9
	4	+		+		-183.6	10.8
	5	+	+	+		-175.9	18.4
	6		+			-171.2	23.2
	7	+		+	+	-165.7	28.7
	8	+	+	+	+	-157.2	37.1

Table A8. Experimental rain events model selection table showing the best model for *Sanionia*, using a linear mixed-effect model. Top-ranked model is marked with bold face. Global models (always including Plot ID as random factor):

Change in NDVI ~ Round x Change in moss water content x Round

Parameter	**Rank**	**Change in moss water content**	**Round**	**Change in moss water content: Round**	**AIC$_c$**	**ΔAIC$_c$**
Change in NDVI	**1**	**+**			**-39.5**	**0**
	2		+		-32.7	6.8
	3	+	+		-26.9	12.5
	4	+	+	+	-13.2	26.3

Table A9. Experimental rain events model selection table showing the best model for *Tomentypnum*, using a linear mixed-effect model. Top-ranked model is marked with bold face. Global models (always including Plot ID as random factor):

Change in NDVI ~ Change in moss water content x Round

Parameter	**Rank**	**Change in moss water content**	**Round**	**Change in moss water content: Round**	**AIC$_c$**	**ΔAIC$_c$**
Change in NDVI	**1**	**+**			**-125.5**	**0**
	2	+	+		-113.7	11.8
	3	+	+	+	-106.8	18.6
	4		+		-99.1	26.4

Table A10a. Natural rain events model estimates (estimate ± SE) for model testing for the effect of natural rain event (explanatory variable) on change in soil moisture (response variable), for *Sanionia*. Model estimates are based on the top-ranked linear mixed effect models. Intercept was removed for easier interpretation of the effect (size) of natural rain (because of the three factor levels).

Response variable	**Vegetation type**	**Event 1**	**Event 2**	**Event 3**
Change in soil moisture (%)	S	1.89 ± 0.78 (t=2.4)*^{ab}	-1.02 ± 0.078 (t=-1.3)^{ac}	4.23 ± 0.78 (t=5.4)*^{bc}

Table A10b. Natural rain events model estimates (estimate ± SE) for the model testing for the effect of natural rain event and treatment (i.e. plots treated with experimental rain), as explanatory variables, on change in soil moisture as response variable, for *Tomentypnum*. Model estimates are based on the top-ranked linear mixed effect models. Intercept was removed for easier interpretation of the effect (size) of natural rain (because of the three factor levels).

Response variable	**Vegetation type**	**Control (Event 1)**	**Control (Event 2)**	**Control (Event 3)**	**Treatment (Event 1)**	**Treatment (Event 2)**	**Treatment (Event 3)**
Change in soil moisture (%)	T	1.89 ± 1.08 (t=1.8)^{b}	3.40 ± 1.08 (t=3.2)*^{c}	6.49 ± 1.08 (t=5.9)*^{bc}	3.15 ± 1.08 (t=2.9)*^{b}	4.66 ± 1.08 (t=4.3)*^{c}	7.75 ± 1.08 (t=7.2)*^{bc}

* = Statistically significance ($P < 0.05$) from 0

a = Statistically significance between Event 1 and Event 2

b = Statistically significance between Event 1 and Event 3

c = Statistically significance between Event 2 and Event 3

Table A11. Experimental rain events model estimates (estimate ± SE) for models testing for the effect of treatment (i.e. plots treated with experimental rain), as explanatory variable, on change in soil moisture as response variable. Intercept correlates to control plots. The model is divided into the two vegetation types *Sanionia* (S) and *Tomentypnum* (T), and model estimates are based on the top-ranked linear mixed effect model.

Response variable	**Vegetation type**	**Control (Round 1)**	**Control (Round 2)**	**Treatment (Round 1)**	**Treatment (Round 2)**
Change in soil moisture (%)	S	-0.98 ± 0.79 (t=-1.2)	-0.05 ± 0.79 (t=-0.1)	0.18 ± 0.79 (t=0.2)	4.53 ± 0.79 (t=5.7)*
	T	1.17 ± 0.85 (t=1.4)	4.60 ± 0.85 (t=5.4)*	5.29 ± 0.85 (t=6.2)*	10.56 ± 0.85 (t=12.4)*

* = statistically significance (P < 0.05) from 0

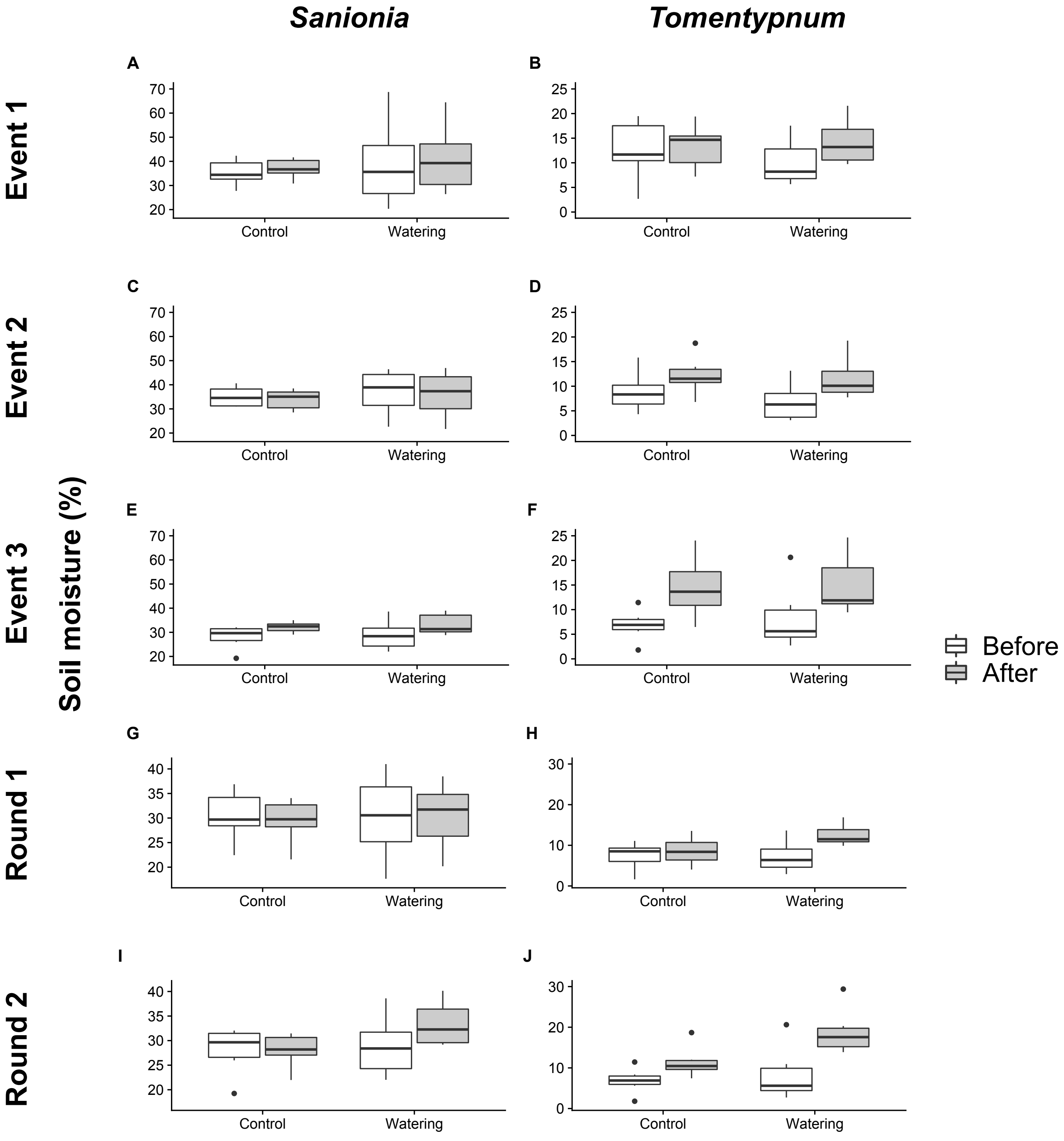

Figure A1. Soil moisture (%) for *Sanionia* (left) and *Tomentypnum* (right) before/after natural rain in Event 1 (A, B), Event 2 (C, D) and Event 3 (E, F), and before/after experimental rain in Round 1 (G, H) and Round 2 (I, J). White boxes indicate values before natural/experimental rain events, grey boxes indicate values after natural/experimental rain events.

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