Online Resource 2: Preanalysis

The *Calluna* life cycle concept revisited – implications for heathland management

Biodiversity and Conservation

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This file contains a brief overview of initial analysis results concerning dataset-inherent correlations and associations. Additionally, they provide further information to effects of study area, management, nitrogen deposition and oceanicity on the vitality of *Calluna* plants.

Study-area related differences in *Calluna* ages and life histories

Patterning of ages in study areas

Initial analysis offered study area-specific patterning of nitrogen deposition (source: UBA 2019) and oceanicity (calculation see below), which is induced by sampling design, with higher nitrogen loads and higher oceanicity in the northwestern sites compared to the eastern and south-eastern sites in Northern Germany.

Oceanicity and nitrogen deposition are highly correlated (Spearman $\rho = 0.92$, Fig. 8, Fig. 9). As a consequence, TD, CKH and FH, located in the Northwest, had nitrogen loads of >17kg/h*y^{-1}, whereas ZW, P, GH, OH located in the Mid-East and East, had only 10-11 kg/h*y^{-1} (Table 1 for abbreviations, c.f. OR 1: Table 11).

Table 1 study area abbreviations used in Fig. 1-3.

abbreviation	Study area
TD	Tinner Dose
CKH	Cuxhavener Küstenheiden
SBD	Suederluegumer Binnenduenen
FH	Fischbeker Heide
B	NATO training area Bergen-Hohne
LH	Lüneburger Heide
NH	Nemitzer Heide
LT	Leussower Heide
MF	Marienfliess
KRH	Kyritz-Ruppiner Heide
OH	Oranienbaumer Heide
RH	Rüthnicker Heide
KS	Kleine Schorfheide
VH	Vietmannsdorfer Heide
GH	Glücksburger Heide
UH	Bundeswehr training area Jägerbrück
P	Prösa
ZW	Zschornoer Wald
DW	Daubaner Wald

In addition, we detected study area-specific patterning in *Calluna* plant age structures (Fig. 1), caused by different site histories and specific management, but probably also by nitrogen loads or oceanicity effects (Table 1). Our results suggest a negative relationship between total *Calluna* plant age and nitrogen deposition (Spearman $\rho < -0.30$, Fig. 1a,c,e,g).

The study-area specific patterns of age are omitted in the final analysis used in the main article, because using study area as random term to correct for spatial autocorrelation removes other study area-specific effects, too.

Comment to Sample size

Sample size differed between study areas due to restricted accessibility to sites or availability of suitable plants to sample. Hence, some study areas lacked in sufficient sampling material (Fig. 1e-h) and are therefore probably underrepresented.

Calculation of Oceanicity

For a measure of climate, we used the Kotilainen's Index of oceanicity K calculated as

$$K = \frac{N * dt}{100\Delta},$$

with N = yearly precipitation in mm, dt = number of vernal or autumnal days with mean temperatures ranging from 0°C – 10°C and Δ = difference between the mean temperature of the warmest and coldest month.

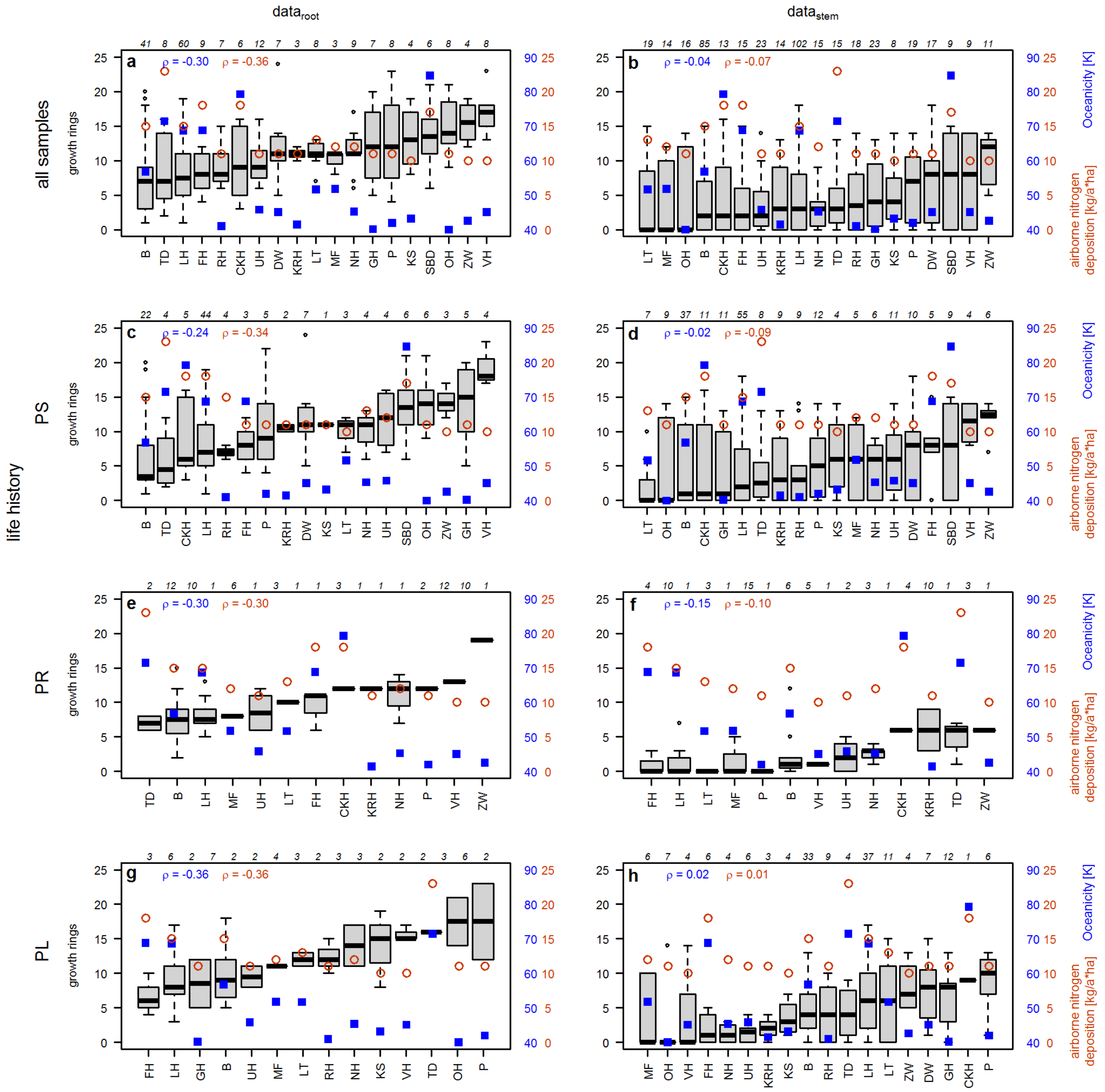

Fig. 1 Growth ring counts in study areas, given for $data_{root}$ (lefthand column, n = 218), and $data_{stem}$ (n = 445, righthand column). The first row includes all plants observed, the second only the plants grown from seed (PS), the third only plant material that is a result from resprouting processes (PR) and the bottom row only plant material from layering trunks or old branches (PL). Study areas are ordered by increasing median of growth ring count. For abbreviations of study areas see Online Resource 1. For all study areas, oceanicity is given as blue quadrats and airborne nitrogen as brown circles. Oceanicity is calculated after Godske (1944), using climate data from 1980-2010 (DWD 2014). Correlation of growth ring counts with Oceanicity and airborne nitrogen deposition is indicated with Spearman's ρ. For values of Oceanicity and airborne nitrogen deposition see Online Resource 1 Table 2. Sample sizes in groups are given in italics above the boxes.

Study-area related differences in vitality attributes

Patterning of vitality attributes in study areas

In the initial analysis, we tested for the potential influence of nitrogen deposition or oceanicity on the vitality attributes, as well as their study area-specific patterning (Fig. 2,3). As described above, nitrogen deposition, oceanicity and study area are coupled, hence study-area-specific patterning of vitality attributes indicate probable effects of nitrogen or oceanicity. In our models, we included study area as a random term to account for spatial autocorrelation effects, but in doing so we also removed the effects of nitrogen deposition and oceanicity. The initial analysis showed no effects of nitrogen deposition and oceanicity on flower density (Fig.2a,b), the amount of total flowers/plant (Fig. 2g,h) and only marginal affects on all other vitality attributes, with Spearman´s ρ ranging between 0.1 and 0.4.

Vitality attributes showed stronger study area-specific differences and correlations with nitrogen and oceanicicty in $data_{root}$ than in $data_{stem}$., indicating that effects of nitrogen and oceancity may interact with total plant age rather than regeneration age.

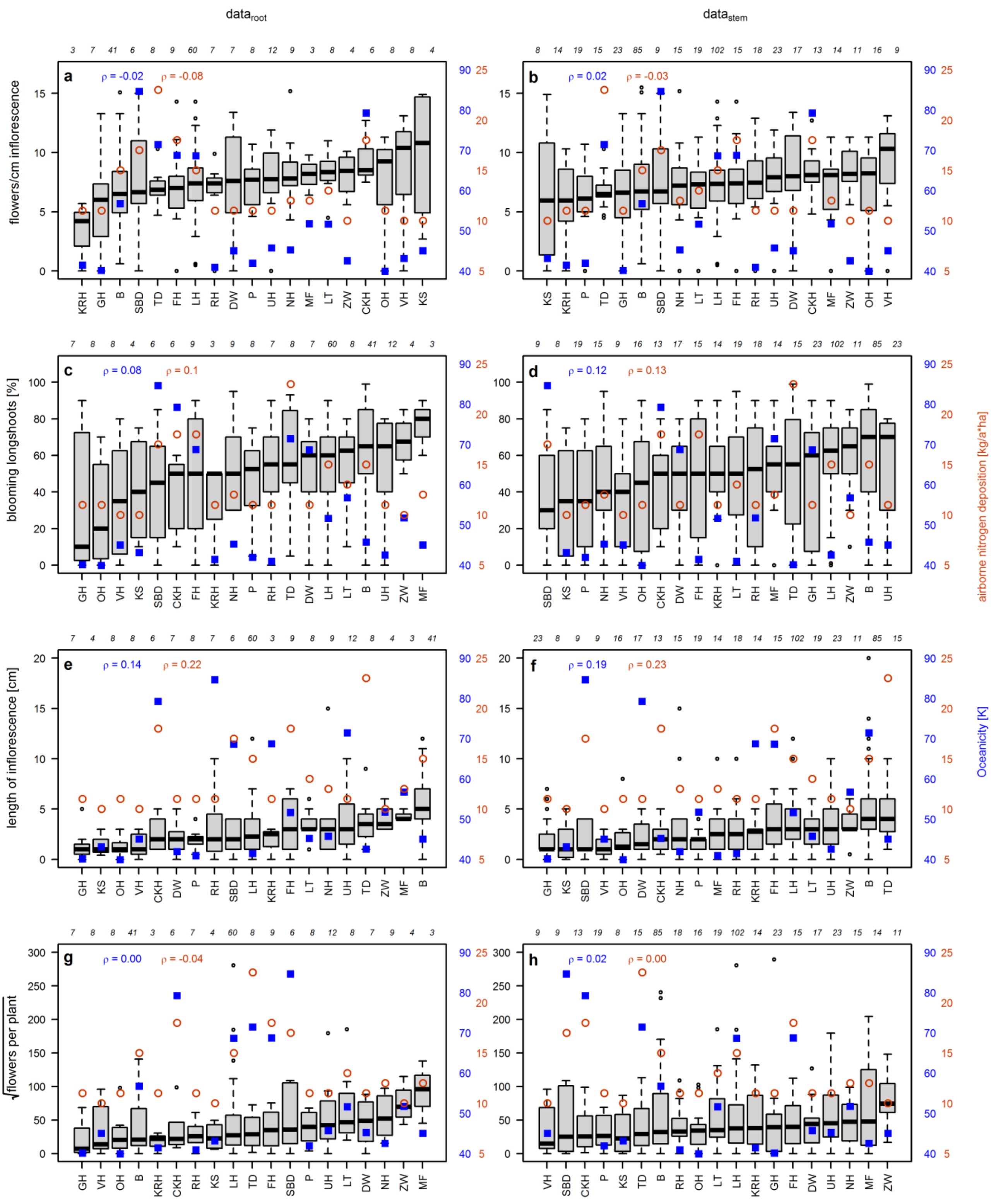

Fig. 2 Vitality attributes in study areas, part 1. Study areas are ordered by increasing median of vitality attribute. For abbreviations of study areas see Online Resource 1. For all study areas, oceanicity is given as blue quadrats and airborne nitrogen as brown circles. Oceanicity is calculated after Godske (1944), using climate data from 1980-2010 (DWD 2014). Correlation of vitality parameter with Oceanicity and airborne nitrogen deposition is indicated with Spearman's ρ, for scatter plots see Online Resource 2 Fig. 9). For values of Oceanicity and airborne nitrogen deposition see Online Resource 1 Table 2. Sample sizes in groups are given in italics above the boxes.

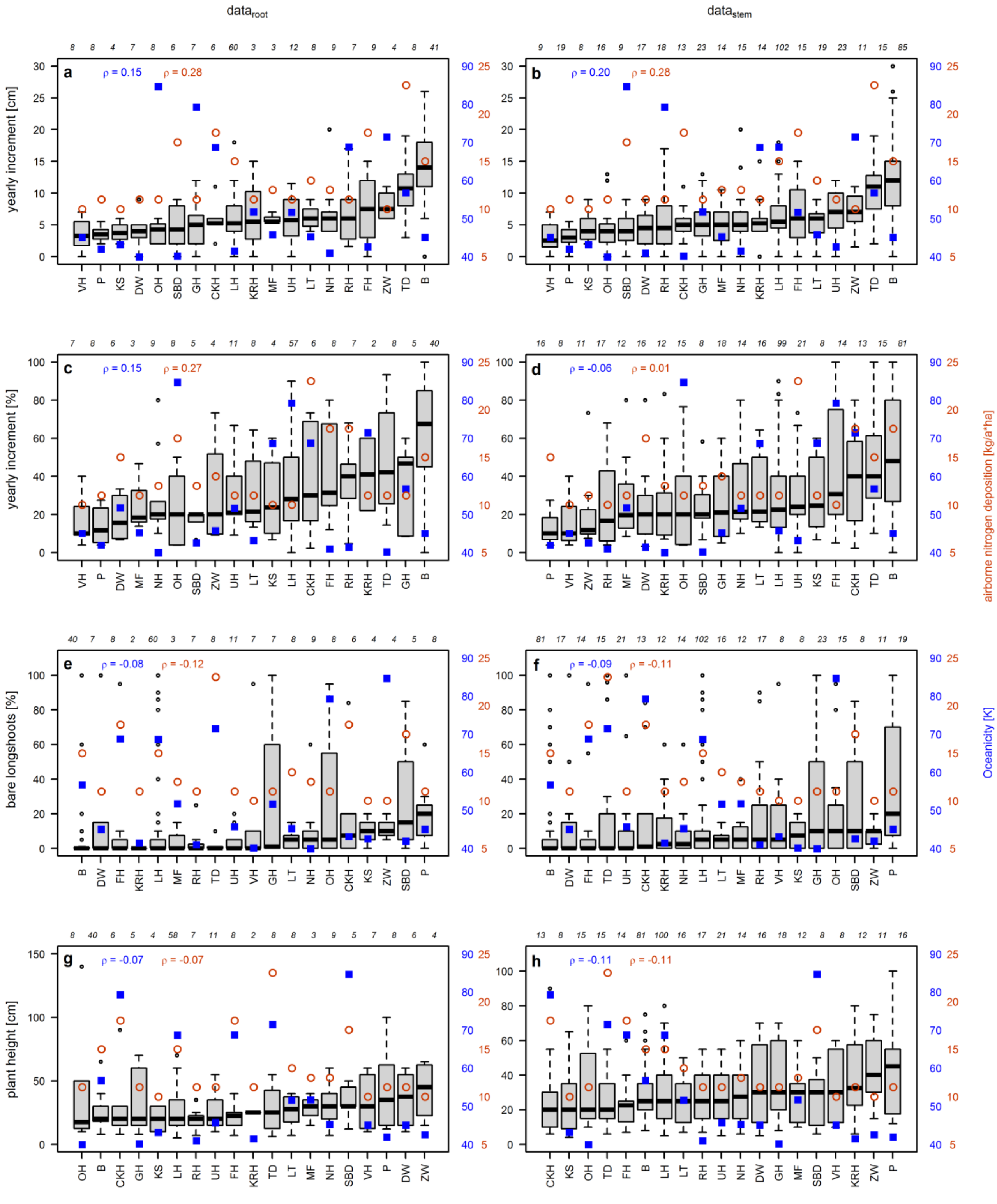

Fig. 3 Vitality attributes in study areas, part 2. Study areas are ordered by increasing median of vitality parameter. For abbreviations of study areas see Online Resource 1. For all study areas, oceanicity is given as blue quadrats and airborne nitrogen as brown circles. Oceanicity is calculated after Godske (1944), using climate data from 1980-2010 (DWD 2014). Correlation of vitality parameter with Oceanicity and airborne nitrogen deposition is indicated with Spearman's ρ, for scatter plots see Online Resource 2 Fig. 9). For values of Oceanicity and airborne nitrogen deposition see Online Resource 1 Table 2. Sample sizes in groups are given in italics above the boxes.

Severe management effects on *Calluna* vitality

Severe management categories comprise Burning (F), Mowing (Ma), Sod-cutting (S) or no application of high-severe biomass disturbance (none) in the past 5 years prior to sampling. In the initial analysis, we applied non-parametric multiple Mann-Whitney U tests to detect significant differences between severe management for each vitality attribute (Fig. 4, 5). Significant differences between categories of severe management indicated effects on vitality attribute that may disturb age-related effects. In these cases, we included severe management as random term in the Linear Mixed Model to partial out management-induced effects.

Of course, age-related effects on vitality are not independent from those of severe management. Any severe biomass disturbance leads to either plant death or regeneration. In the latter, rejuvenation of aboveground biomass is the driver of vitality, and we assume the disturbance-driven rejuvenation *per se* to be of higher importance for the vitality than the severe management category-driven differences. This turned out to be true for all vitality attributes except for the length of inflorescences (Fig. 4e,f), the proportion of bare long shoot tips (Fig. 5b), as well as the relative and total yearly increment (Fig.5 c-f). Fire promoted significantly longer inflorescences and growth rates. Mowing increased the proportion of bare long shoot tips significantly, due to the remaining erect stems after cutting. With including severe management as random term in the LMMs for inflorescence length, bare long shoots tips and the yearly increments (total+relative), the specific effects of the management categories were omitted and the only age-related effects remained in the model.

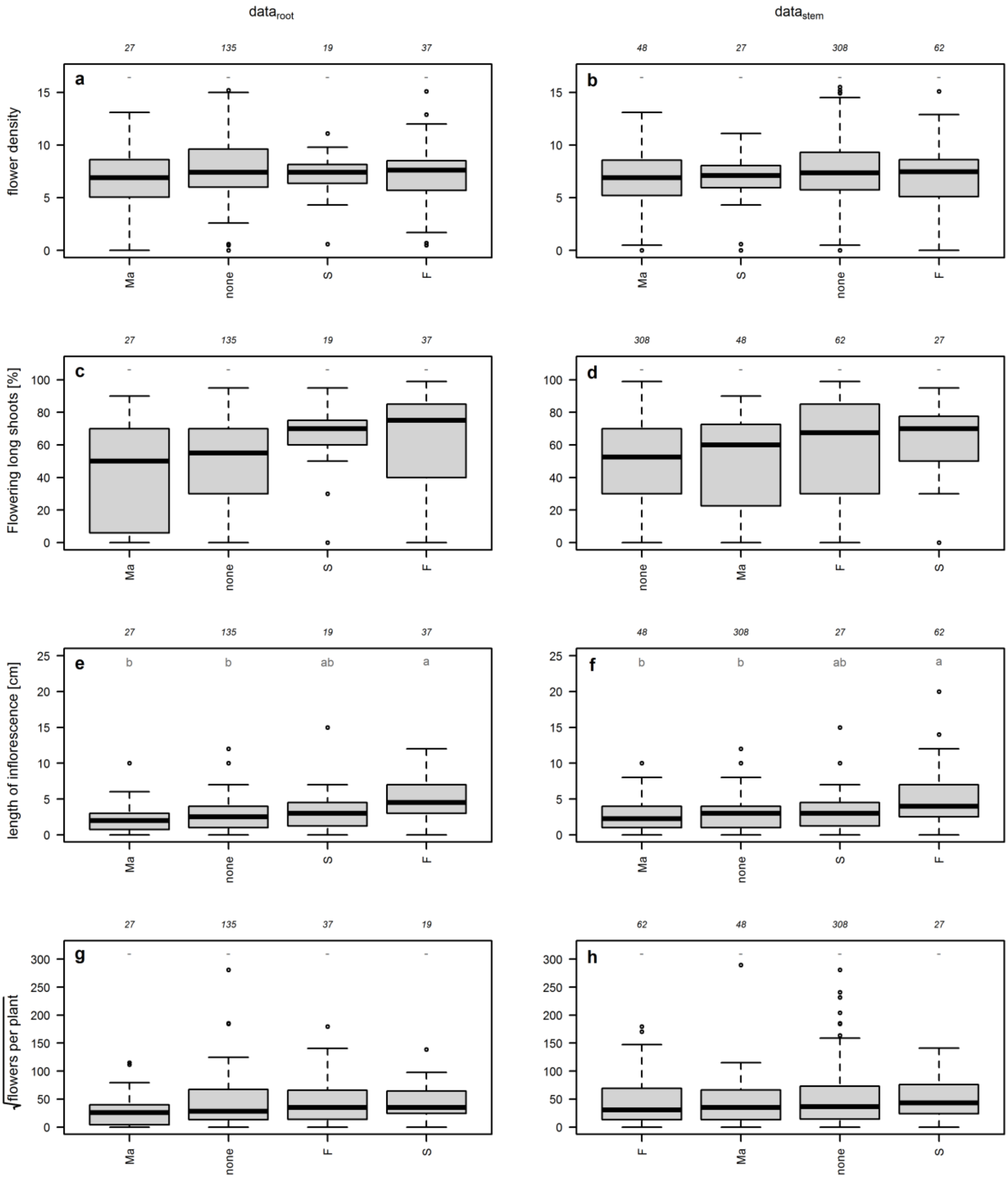

Fig. 4 Vitality attributes depending on intense management, part 1. Significant differences ($p \leq 0.05$) are detected with multiple Mann-Whitney U tests and are indicated by different letters. Sample sizes in groups are given in italics above the boxes. Abbreviations: Ma = site was at least one time mowed within the past 5 years, none = no intense management on the site within the past 5 years, S = site was sod cut or plagged within the past five years, F = site was at least one time burnt in the past 5 years. Managements are ordered by increasing median.

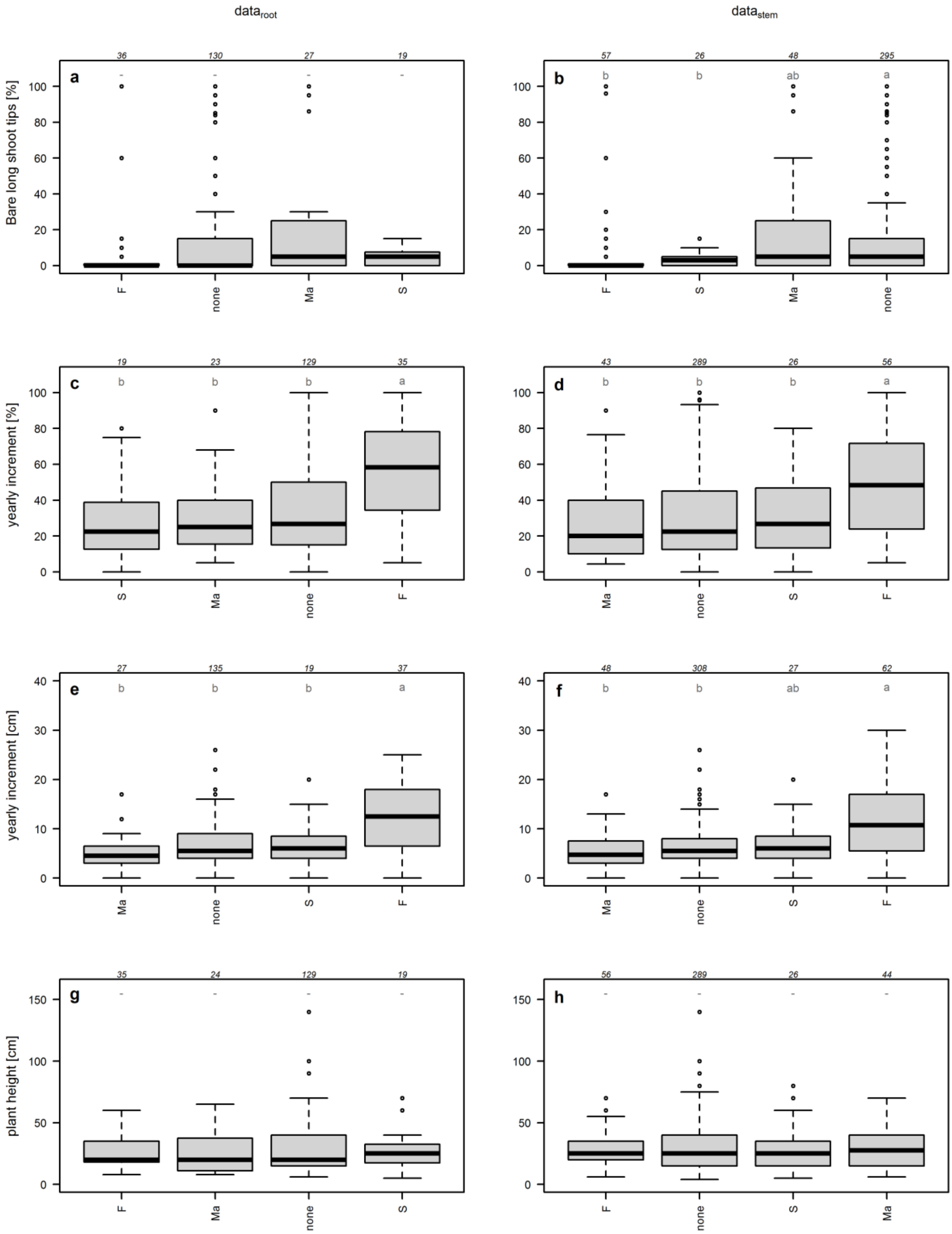

Fig. 5: Vitality attributes depending on intense management, part 2. Significant differences ($p \leq 0.05$) are detected with multiple Mann-Whitney U tests and are indicated by different letters. Sample sizes in groups are given in italics above the boxes. Abbreviations: Ma = site was at least one time mowed within the past 5 years, none = no intense management on the site within the past 5 years, S = site was sod cut or plagged within the past five years, F = site was at least one time burnt in the past 5 years. Managements are ordered by increasing median.

Grazing effects on *Calluna* vitality

In the initial analysis, we applied non-parametric multiple Mann-Whitney U tests to detect significant differences between grazing categories for each vitality attribute (Fig. 6, 7). The grazing categories comprised non-grazed sites for at least 5 years (no), sites browsed by free-ranging deer (deer), extensive interval or year-round grazing by cattle and/or horses (horses/cattle), traditional year-round shepherding (sheep trad), sites of intensive sheep grazing in traditional year-round shepherding (e.g. near barns or on daily used trails, sheep trad +), sheep temporarily fenced with high grazing pressure (sheep fenced).

Significant differences between those categories indicated grazing effects on vitality attribute that may disturb age-related effects. In these cases, we included grazing as random term in the Linear Mixed Model to partial out grazing-induced effects.

Only length of inflorescences (Fig. e) and yearly increments (Fig. 7c-f) showed significant differences between grazing regimes. Hereby, it was the grazing activity itself that reduced the lengths of the yearly growth and inflorescence rather than the specific type of management. High and frequent grazing pressure supports high relative growth rates (Fig. 7c,d) because plants heavily grazed regenerate in flat-growing mats, resulting in a high proportion of foliated long shoot to the total plant height.

With the inclusion of grazing as a random term in the LMMs for the inflorescence length and the yearly increments (total+relative), the specific effects of the grazing regimes were removed and the only age-related effects remained in the model. Additionally, study area-specific grazing conditions are partialled out due to including study area as random.

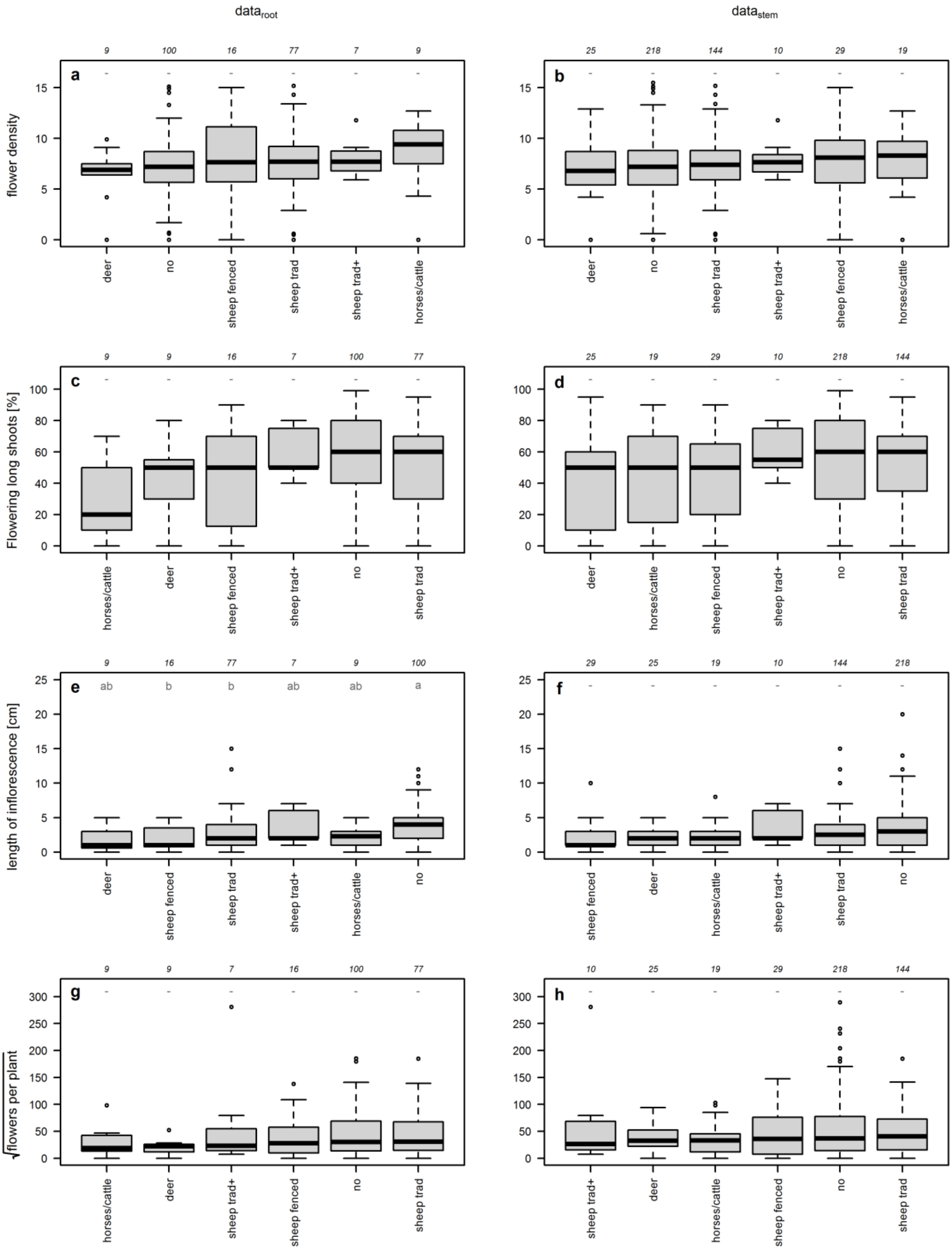

Fig. 6: Vitality attributes depending grazing, part 1. Significant differences (p ≤ 0.05) are detected with multiple Mann-Whitney U tests and are indicated by different letters. Sample sizes in groups are given in italics above the boxes. Grazing categories: deer = browsing activities, mainly of red deer and fallow deer; horses/cattle = extensive interval or year-round grazing by cattle and/or horses; sheep trad = traditional shepherding; sheep trad + = sites of intensive sheep grazing in traditional shepherding (e.g. near barns or on daily used trails); sheep fenced = sheep temporarily fenced with high grazing pressure; no = no grazing activities known or observed in the past 5 years. Grazing categories are ordered by increasing median.

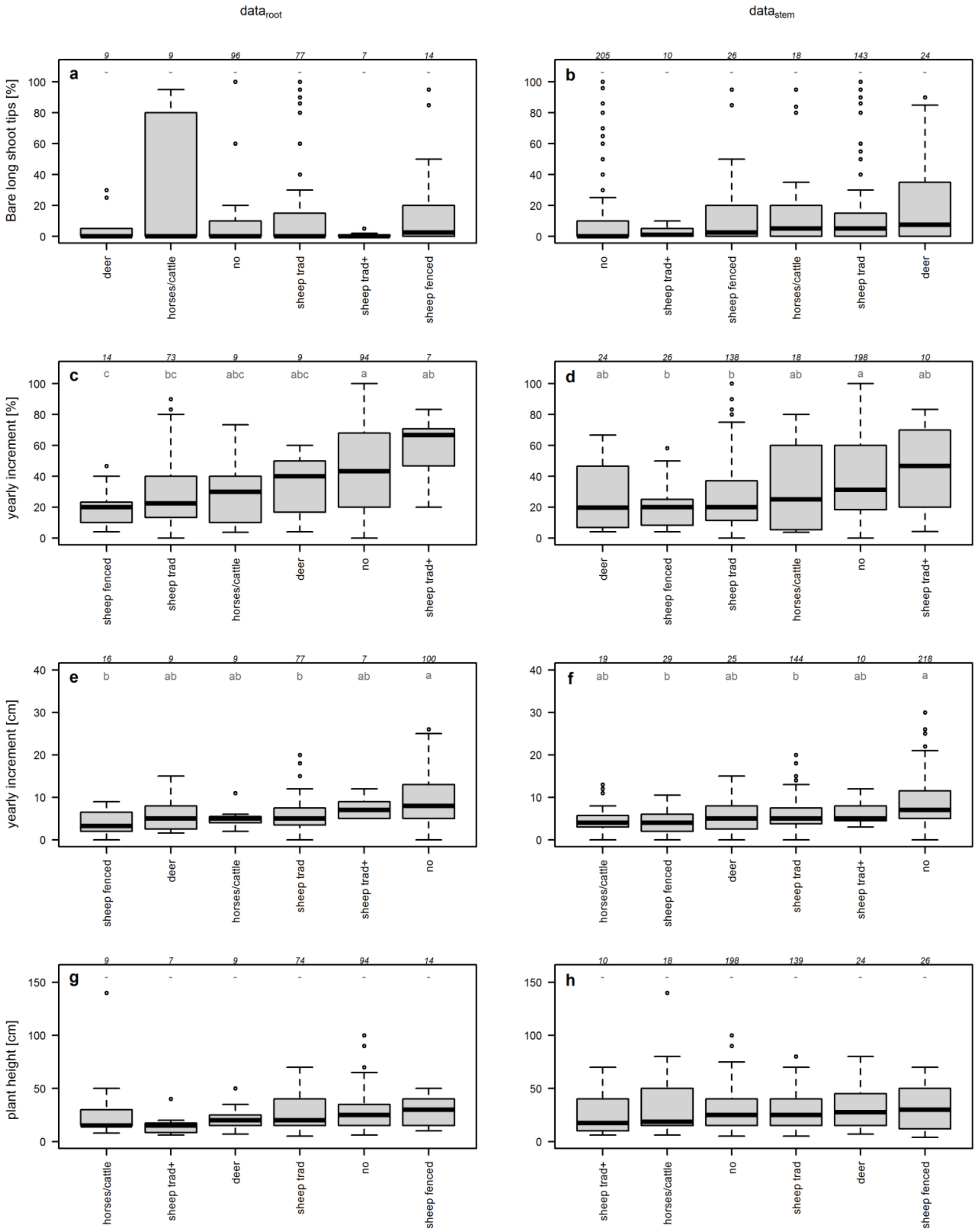

Fig. 7 Vitality attributes depending grazing, part 2. Significant differences ($p \leq 0.05$) are detected with multiple Mann-Whitney U tests and are indicated by different letters. Sample sizes in groups are given in italics above the boxes. Grazing categories: deer = browsing activities, mainly of red deer and fallow deer; horses/cattle = extensive interval or year-round grazing by cattle and/or horses; sheep trad = traditional shepherding; sheep trad + = sites of intensive sheep grazing in traditional shepherding (e.g. near barns or on daily used trails); sheep fenced = sheep temporarily fenced with high grazing pressure; no = no grazing activities known or observed in the past 5 years. Grazing categories are ordered by increasing median.

Correlation matrices

All numerical variables used in the LMM procedure were checked for dataset-inherent correlations by Spearman´s ρ for detecting collinearity and through visual checks of scatter plots (Fig. 8 for $data_{root}$, Fig.9 for $data_{stem}$).

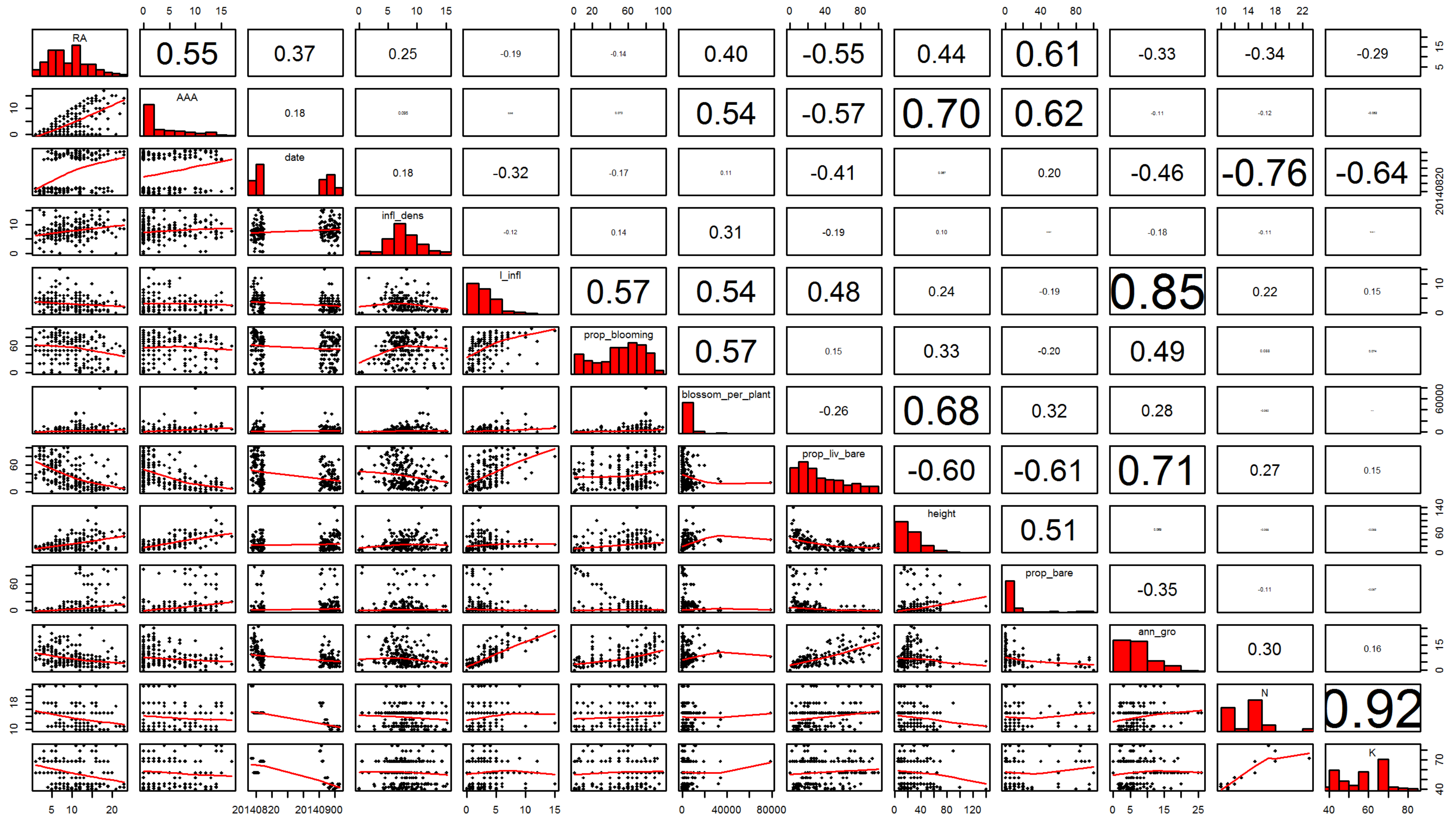

Fig. 8 Correlation matrix for $data_{root}$ (RA = rootstock growth ring counts, AAA = branches growth ring counts), date of sampling, vitality attributes (infl_dens = inflorescence density, l_infl = length of inflorescence [cm], prop_blooming = flowering long shoots [%], blossom_per_plant = number of flowers per plant, prop_liv_bare = relative yearly increment [%], height = maximum plant height [cm], prop_bare = bare long shoot tips [%], ann_gro = total yearly increment [cm]) as well as nitrogen deposition (N) and Oceanicity (K). Spearman's ρ given and font size is adjusted to total positive or negative correlation strength. Correlations are based on the total dataset (n = 445), therefore slight deviations from the values given in Fig 3 and Fig 4 are due to the use of subdatasets there. Scatter plots show smoothed regression lines (red) using the lowess() function (R stats package).

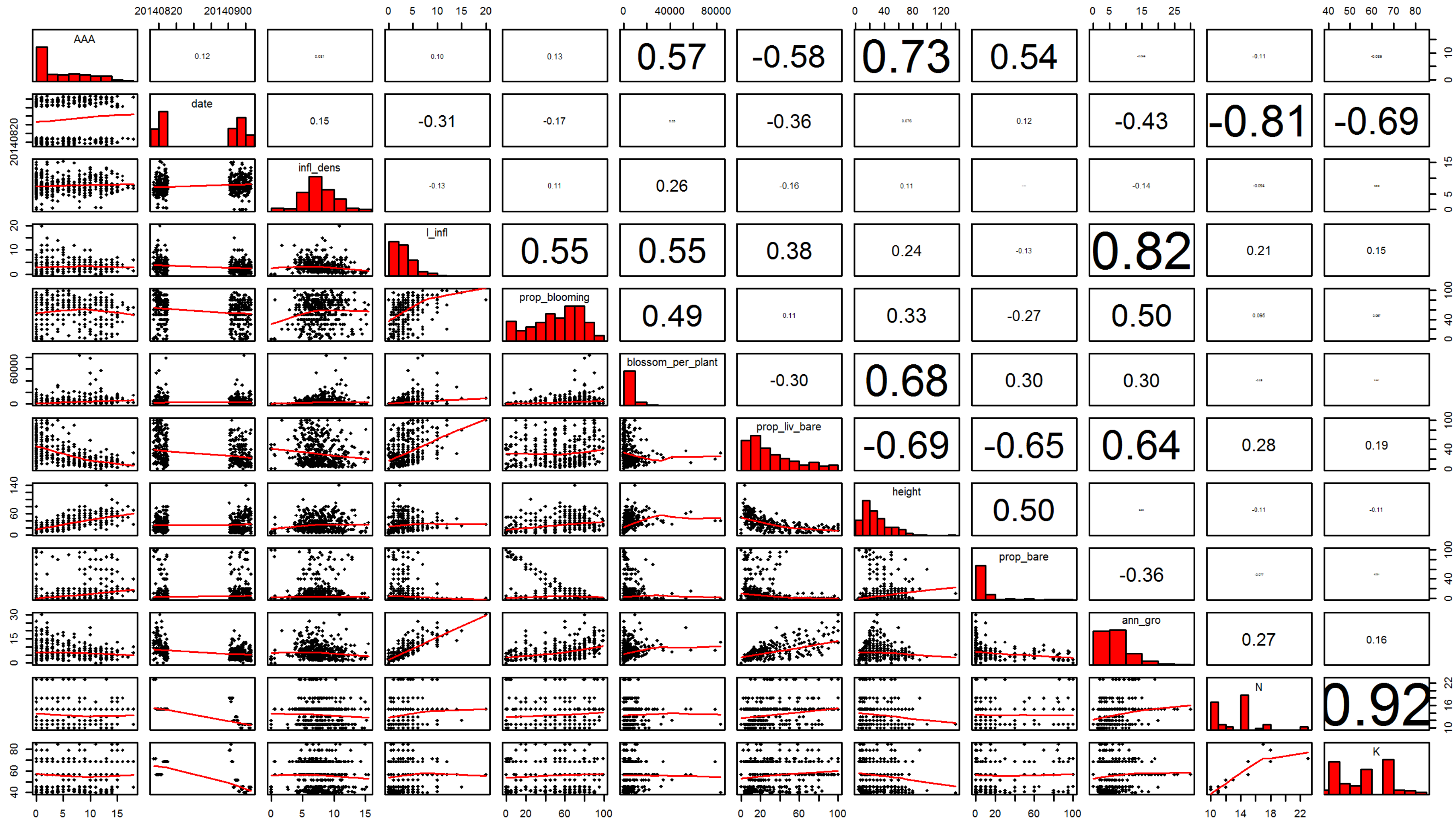

Fig. 9 Correlation matrix for $data_{stem}$ (RA = rootstock growth ring counts, AAA = branches growth ring counts), date of sampling, vitality attributes (infl_dens = inflorescence density, l_infl = length of inflorescence [cm], prop_blooming = flowering long shoots [%], blossom_per_plant = number of flowers per plant, prop_liv_bare = relative yearly increment [%], height = maximum plant height [cm], prop_bare = bare long shoot tips [%], ann_gro = total yearly increment [cm]) as well as nitrogen deposition (N) and Oceanicity (K). Spearman's ρ given and font size is adjusted to total positive or negative correlation strength. Correlations are based on the total dataset (n = 445), therefore slight deviations from the values given in Fig 3 and Fig 4 are due to the use of subdatasets there. Scatter plots show smoothed regression lines (red) using the lowess() function (R stats package).

References

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