TOS DESIGN OPTIMIZATION: HERBACEOUS CLIP HARVEST

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1 RELATED DOCUMENTS AND ACRONYMS

1.1 Reference Documents

RD[01]	NEON.DOC.000001	NEON Observatory Design
RD[02]	NEON.DOC.002652	NEON Data Products Catalog
RD[03]	NEON.DOC.000914	TOS Science Design for Plant Biomass and Productivity
RD[04]	NEON.DOC.014037	TOS Protocol and Procedure: Measurement of Herbaceous Biomass

1.2 Acronyms

Acronym	Definition
AGB	Above-Ground Biomass
ANPP	Aboveground Net Primary Productivity
AOS	Aquatic Observation System
NLCD	National Land Cover Database
TOS	Terrestrial Observation System
TWG	Technical Working Group

2 BACKGROUND AND GOALS

2.1 Description of sample design and available data

Clip-harvests of herbaceous aboveground biomass (AGB) contribute to estimates of annual Aboveground Net Primary Productivity (ANPP) at plot, site, and continental scales, and provide essential data for understanding vegetative C fluxes over time. Distributed Plots are sampled every 5 years at each site (n=20 max), and this sampling effort is focused on enabling site-level AGB estimates. Tower Plots are sampled annually, and the goal is to enable ANPP estimates from the dominant vegetation at the site. At sites actively managed for grazing, the original sampling design specified a 4-week sampling interval for clip-harvest bouts in order to estimate consumption of AGB by herbivores and the compensatory growth response to grazing. Because Tower Plot sampling at grazed and ungrazed sites represents a much larger labor investment than Distributed Plot sampling, the optimization analyses in this report are focused on Tower Plot sampling.

At sites with short-stature vegetation, a maximum of n=30 20m x 20m Tower Plots are established, and within each plot one randomly located 2m x 0.1m 'clip-strip' is harvested per bout. Sites with tall-stature vegetation have a maximum of n=20 40m x 40m Tower Plots, and two clip-strips are harvested per bout, one from each of two randomly selected 20m x 20m subplots within the larger plot. Clip strips are moved to new random locations each bout, and at sites not managed for grazing there is typically one bout per year. At sites with grazing management, an additional clip strip per plot or subplot is placed under a small portable grazing exclosure, and the number of bouts per season is determined by the 4-week sampling interval and the length of the grazing season.

Biomass and productivity produced by herbaceous plants at a site over the course of a year are reported as grams dry mass per clip-harvest strip, which are readily converted to grams per meter squared. Samples are collected in the field and sorted into six functional groups:

- Bryophytes
- Cool-season graminoids (C3)
- Warm-season graminoids (C4)
- Nitrogen-fixing plants (typically Fabaceae spp. but may include some woody-stemmed species)
- Forbs (not N-fixing)
- Woody-stemmed plamts (diameter < 1 cm at decimeter height)

At sites managed for grazing, only the peak biomass bout is sorted to functional group, and total biomass is reported for all other bouts. All samples are dried to constant mass and weighed. Dry mass measurements are reported in grams with a minimum precision of 0.01 g.

2.1.1 2018 Sampling Reduction

Prior to the 2018 sampling season, all sites managed for grazing were sampled for herbaceous biomass on a 4-week interval with the clip-harvest method. Sampling reductions for 2018 were identified prior to completion of analyses documented here, and with input from the Plant Biomass and Productivity TWG. Modifications included increasing the sampling interval from 4-weeks to 8-weeks at sites thought to have moderate productivity, where it was hypothesized that consumption could not be detected with a 4-week interval. At grazed sites where productivity was thought to be very low, sampling was reduced to 1 or 2 bouts per year, with exclosures at these sites allowing an assessment of relative grazing intensity but possibly not consumption (Table 1).

Table 1: Summary of 2018 sampling modifications at grazed sites made with TWG guidance but prior to completion of optimization analyses.

Domain	Site	Site Type	Sampling Strategy
D10	CPER	Low productivity	2 bouts, each sorted to functional group. One late spring (C3s), one late summer (C4s).
D13	MOAB	Low productivity	1 bout at peak biomass, sorted to functional group.
D14	SRER	Low productivity	2 bouts, each sorted to functional group. One early spring, one late summer.
D09	DCFS	Mid productivity	8-week sampling interval, peak biomass bout sorted to functional group.
D09	NOGP	Mid productivity	8-week sampling interval, peak biomass bout sorted to functional group.
D09	WOOD	Mid productivity	8-week sampling interval, peak biomass bout sorted to functional group.
D17	SJER	Mid productivity	8-week sampling interval, peak biomass bout sorted to functional group.

Domain	Site	Site Type	Sampling Strategy
D04	LAJA	High productivity	No change: 4-week sampling interval, peak biomass bout sorted to functional group.
D06	KONZ	High productivity	No change: 4-week sampling interval, peak biomass bout sorted to functional group.
D11	CLBJ	High productivity	No change: 4-week sampling interval, peak biomass bout sorted to functional group.
D17	TEAK	High productivity	No change: 4-week sampling interval, peak biomass bout sorted to functional group.

2.1.2 Optimization Analyses

Optimization analyses utilized L1 Herbaceous Biomass and Productivity data publicly available on the NEON Data (DP1.10023)(Table 2).

Table 2: Summary of sites and data included in Herbaceous Biomass and Productivity optimization analyses. Grazing = site managed for grazing; Year Range = years contributing data to analysis; Total Years = total number of years of data analyzed; Tower Plot Size = dimensions of established Tower Plots; Clips Per Plot = number of herbaceous clip harvests performed per plot per bout; Tower NLCD Class = NLCD class of vegetation in Tower footprint, * = multiple NLCD types present and dominant type is listed.

Domain	Site	Site Name	State	Grazing	Year Range	Total Years	Tower Plot Size	Clips Per Plot	Tower NLCD Class
D01	BART	Bartlett Experimental Forest	NH	N	2014-2017	4	40m x 40m	2	Deciduous forest*
D01	HARV	Harvard Forest	MA	N	2013-2017	5	40m x 40m	2	Mixed forest*
D02	BLAN	Blandy Experimental Farm	VA	N	2015-2018	4	20m x 20m	1	Cultivated crops*
D02	SCBI	Smithsonian Conservation Biology Institute	VA	N	2014-2017	4	40m x 40m	2	Deciduous forest
D02	SERC	Smithsonian Environmental Research Center	MD	N	2015-2018	4	40m x 40m	2	Deciduous forest

Domain	Site	Site Name	State	Grazing	Year Range	Total Years	Tower Plot Size	Clips Per Plot	Tower NLCD Class
D03	DSNY	Disney Wilderness Preserve	FL	N	2014-2017	4	20m x 20m	1	Pasture / Hay
D03	JERC	Jones Ecological Research Center	GA	N	2014-2018	5	40m x 40m	2	Evergreen forest*
D03	OSBS	Ordway-Swisher Biological Station	FL	N	2013, 2014, 2017	3	40m x 40m	2	Evergreen forest
D04	GUAN	Guanica Forest	PR	N	2015-2017	3	40m x 40m	2	Evergreen forest
D04	LAJA	Lajas Experimental Station	PR	Y	2016-2017	2	20m x 20m	2	Pasture / Hay
D05	STEI	Steigerwaldt Land Services	WI	N	2015-2017	3	40m x 40m	2	Deciduous forest
D05	TREE	Treehaven	WI	N	2015-2017	3	40m x 40m	2	Mixed forest*
D05	UNDE	University of Notre Dame Environmental Research Center	MI	N	2015-2017	3	40m x 40m	2	Deciduous forest*
D06	KONA	Konza Prairie Biological Station Agricultural	KS	N	2017	1	20m x 20m	1	Cultivated crops
D06	KONZ	Konza Prairie Biological Station	KS	Y	2015-2017	3	20m x 20m	2	Grassland herbaceous*
D06	UKFS	University of Kansas Field Station	KS	N	2015-2017	3	40m x 40m	2	Deciduous forest*
D07	GRSM	Great Smoky Mountain National Park	TN	N	2015-2017	3	40m x 40m	2	Deciduous forest*

Domain	Site	Site Name	State	Grazing	Year Range	Total Years	Tower Plot Size	Clips Per Plot	Tower NLCD Class
D07	ORNL	Oak Ridge National Laboratory	TN	N	2014-2017	4	40m x 40m	2	Deciduous forest
D08	DELA	Dead Lake	AL	N	2015-2017	3	40m x 40m	2	Deciduous forest*
D08	LENO	Lenoir Land-ing	AL	N	2016-2017	2	40m x 40m	2	Woody wet-lands*
D08	TALL	Talladega National Forest	AL	N	2014-2017	4	40m x 40m	2	Evergreen forest*
D09	DCFS	Dakota Coteau Field Station	ND	Y	2017	1	20m x 20m	2	Grassland herba-ceous*
D09	NOGP	Northern Great Plains Research Laboratory	ND	Y	2016-2017	2	20m x 20m	2	Grassland herba-ceous*
D09	WOOD	Woodworth	ND	Y	2014, 2016, 2017	3	20m x 20m	2	Grassland herba-ceous
D10	CPER	Central Plains Experimental Range	CO	Y	2013-2018	6	20m x 20m	2	Grassland herba-ceous
D10	RMNP	Rocky Moun-tain National Park	CO	N	2017-2018	2	40m x 40m	2	Evergreen forest*
D10	STER	Sterling	CO	N	2013-2018	6	20m x 20m	1	Cultivated crops
D11	CLBJ	Caddo LBJ National Grassland	TX	Y	2016-2017	2	20m x 20m	2	Deciduous forest*
D11	OAES	Klemme Range Re-search Station	OK	N	2015-2017	3	20m x 20m	1	Shrub scrub*
D13	MOAB	Moab	UT	Y	2015-2017	3	20m x 20m	2	Shrub scrub*

Domain	Site	Site Name	State	Grazing	Year Range	Total Years	Tower Plot Size	Clips Per Plot	Tower NLCD Class
D13	NIWO	Niwot Ridge LTER	CO	N	2015-2017	3	20m x 20m	1	Grassland herba-ceous*
D14	JORN	Jornada LTER	NM	N	2015, 2017	2	20m x 20m	1	Shrub scrub
D14	SRER	Santa Rita Experimental Range	AZ	Y	2016-2018	3	40m x 40m	4	Shrub scrub
D15	ONAQ	Onaqui	UT	N	2014-2018	5	20m x 20m	1	Shrub scrub*
D16	ABBY	Abby Road	WA	N	2016-2017	2	40m x 40m	2	Evergreen forest*
D16	WREF	Wind River Experimental Forest	WA	N	2017	1	40m x 40m	2	Evergreen forest
D17	SJER	San Joaquin Experimental Range	CA	Y	2017-2018	2	40m x 40m	4	Evergreen forest*
D18	BARR	Barrow Arc-tic Science Consortium	AK	N	2017	1	20m x 20m	1	Emergent herba-ceous wet-lands*
D18	TOOL	Toolik LTER	AK	N	2017	1	20m x 20m	1	Sedge herba-ceous
D19	BONA	Caribou Creek / Bonanza Creek LTER	AK	N	2017	1	40m x 40m	2	Deciduous forest*
D19	DEJU	Delta Junction	AK	N	2016-2017	2	40m x 40m	2	Evergreen forest*
D19	HEAL	Healy	AK	N	2015-2017	3	20m x 20m	1	Dwarf scrub*
D20	PUUM	Pu'u Ma'akala	HI	N	NA	0	40m x 40m	2	Evergreen forest

2.2 Analytical Goals

Statistically rigorous analyses are needed to assess the capacity of NEON data to address Observatory goals and to guide sampling design optimization efforts. Initial spatial and temporal sampling designs for the NEON Terrestrial Observation System (TOS) and Aquatic Observation System (AOS) were developed in collaboration with Technical Working Groups (TWGs) comprised of community experts, and were captured in Science Design documents (RD[01], etc.). The initial designs relied on analysis of published datasets (where relevant), analysis of NEON prototype data collection efforts, and subject matter expertise.

Analysis and evaluation of the data generated by these designs provides a feedback loop that enables assessment of the Designs relative to Observatory goals. Moreover, results of these analyses will allow the NEON TOS and AOS to effectively prioritize sampling costs in the face of uncertain future funding levels. As the NEON Observatory matures and moves into full operations, it is critical for TOS and AOS initial design assumptions to be tested with multiple years of data collected from NEON sites. At a high-level, analyses must:

- Describe where the data support reduction of TOS and AOS sampling effort without compromising NEON's ability to meet design requirements (e.g., target sites for reduction in sampling effort, spatial scales where replication is not necessary, etc.).
- Evaluate effects of design modifications on uncertainty and ability to detect year-to-year changes for key response variables (e.g., effects of reduced spatial and/or temporal sampling effort).

Specification of analyses suitable for evaluating the efficacy of the NEON TOS and AOS sampling designs required development of specific questions. Power analyses and sampling simulations were then used to determine the degree to which design modifications affected the ability of the data to address those questions. Questions and analytical approaches were developed in consultation with NEON TWGs comprised of subject matter experts selected from the ecological community. Key questions to address for Herbaceous Biomass and Productivity sampling are:

1. Can we detect consumption at grazed sites where exclosures are utilized? At grazed sites we focus on optimizing the temporal components of sampling, and more specifically, the number of sampling bouts within a season. A 4-week sampling interval should not be utilized at sites where an 'exclosure' effect cannot be detected.

2. Where is the variability in the data? Specifically, what proportion of the variance at each site can be attributed to year, NLCD Class, plot or subplot?

   Understanding the components of variance provides a critical component of the actionable directions for modifying sampling size by providing answers to questions such as:

   - At what spatial scale does the sample design capture the most variation?
   - How do variance components differ among sites?
   - Does a site's NLCD land cover classification predict variance components?

   For example, at sites with 40m x 40m plots and tall-stature vegetation that are not managed for grazing, it may be possible to eliminate within-plot replication if variance partitioning indicates this component of the spatial design consistently fails to explain variation in the data across sites.

3. Is it possible to detect meaningful interannual variation in key response variables?

   If the current sampling effort has the statistical power to detect naturally occurring change among years, then it is possible the sampling effort may be reduced while maintaining the ability to detect change.

4. Can a specified amount of year-to-year change in aboveground herbaceous production be detected at a given site? At sites not managed for grazing, what sample size is needed to detect a 20% change in total mass from year to year? Is there sufficient power to detect year-to-year changes (20%) in herbaceous AGB after reducing sampling effort from 20 to 30 plots per site to 5 to 10 plots per site?

   Here, we assume that a design capable of detecting 20% year-to-year change at a site will also be well-poised to detect change of a similar magnitude over longer time periods. We do not have sufficient data at this time to parameterize longer-term temporal variability in herbaceous biomass and we have therefore not quantitatively tested this assumption with more complex simulated time series.

   At grazed sites, the need to calculate consumption as the mean difference between 'exclosed' and 'ambient' clip-harvests within each bout means that a simple power analysis is not suitable to assess the design's ability to assess a 20% change in productivity. Due to budget and schedule limitations, we have therefore focused power analyses presented here on sites without managed livestock.

3 METHODS AND RESULTS

3.1 Data Acquisition

All data for these analyses are published and publicly available. Data were pulled from the NEON Data Portal on 2018-10-15.

3.2 Detecting consumption of herbaceous AGB with exclosures

3.2.1 Response variable, test specifics

The response variable is dry mass of herbaceous biomass inside and outside of grazing exclosures.

3.2.2 Methods

To assess the effect of exclosures on standing biomass, we fit the following mixed model to predict standing biomass at each site:

$$Y \sim f\_exclosure + (1|year/boutNumber) + (1|plotID)$$

Where:

- Y = Log(x+1) transformed standing biomass
- `exclosure` is a fixed effect
- `boutNumber` and `plotID` are random factors

3.2.3 Results

The fixed effect of exclosure is positive at sites where it is detectable ($p < 0.05$), demonstrating that clip-strips protected by portable exclosures accumulate greater AGB compared to unprotected, ambient clip-strips (Table 3, 'Estimate' column). The results indicate that a difference in standing biomass between exclosed and ambient clip-strips (a rough proxy for consumption by grazers) can be detected at LAJA, DCFS, NOGP, WOOD, CPER, and SJER. Using a 4-week interval, exclosures had no effect on clip-harvested AGB at KONZ, MOAB, and SRER.

Table 3: Estimate of effect size of exclosure on log (x+1) measurements of herbaceous AGB at each NEON site where exclosures were used.

Domain	Site	Estimate	df	F-value	p-value
D04	LAJA	0.3235	841	28.79	0
D06	KONZ	0.0395	286.6	0.69	0.406
D09	DCFS	0.4652	138.9	30.21	0
D09	NOGP	0.1586	393.8	11.12	0.001
D09	WOOD	0.4391	276.3	62.53	0
D10	CPER	0.073	774.7	5.3	0.021
D13	MOAB	-0.0638	791.5	2.87	0.09
D14	SRER	-0.1264	107.3	0.24	0.626
D17	SJER	0.2016	699.2	19.05	0

3.3 Herbaceous biomass variance components analysis

For each site with sufficient qualifying data, the analysis partitions the variance of herbaceous biomass production and illuminates patterns of variability across both spatial and temporal scales.

3.3.1 Response variable, test specifics

The response variable is dry mass of herbaceous biomass at peak biomass. At grazed sites with > 1 bout, the bout with greatest herbaceous AGB was selected for analysis. For grazed site data to be comparable with sites without livestock, clip-strips protected by exclosures were removed from this analysis.

3.3.2 Methods

We used linear mixed effects models (lme4 package for R) to partition variance in observed AGB among spatial (`nlcdClass`, `plotID`, `subplotID`) and temporal (`year`) grouping factors. This analysis was carried out at each site for each herbaceous functional group defined in Section 2.1, as well as all functional groups combined. The analysis was based on the following model:

$$Y \sim 1 + (1|nlcdClass) + (1|plotID : nlcdClass) + (1|subplotID : plotID : nlcdClass) + (1|year)$$

Where:

- Y = Log(x+1) transformed herbaceous AGB
- `nlcdClass`, `plotID`, `subplotID`, and `year` are all random factors among which variance was partitioned

3.3.3 Results

The total variance in herbaceous standing biomass was highly variable across sites and functional groups (Figure 1). Figure 2 examines the proportional variance explained by random factors in the model. Notable patterns across sites include:

- The `NLCD class` was the most important variance component of total herbaceous standing biomass in 8 sites, and for specific functional groups in an additional 10 sites.
- The spatial `plot` variable was the most important variance component of total herbaceous standing biomass at 13 sites.
- The spatial `subplot` variable explained the most variation at 4 sites.
- The temporal `year` variable explained the most variation at 11 sites.

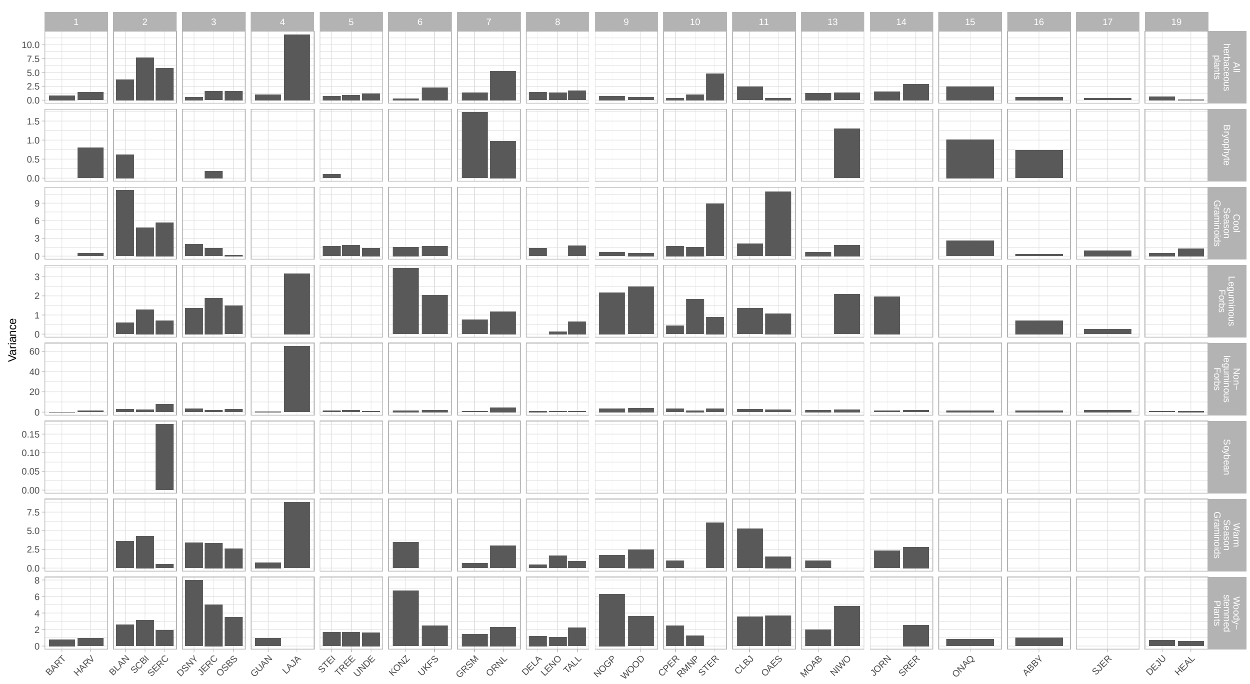

Figure 1: Variance of standing herbaceous AGB at each site for total AGB, as well as for each functional group.

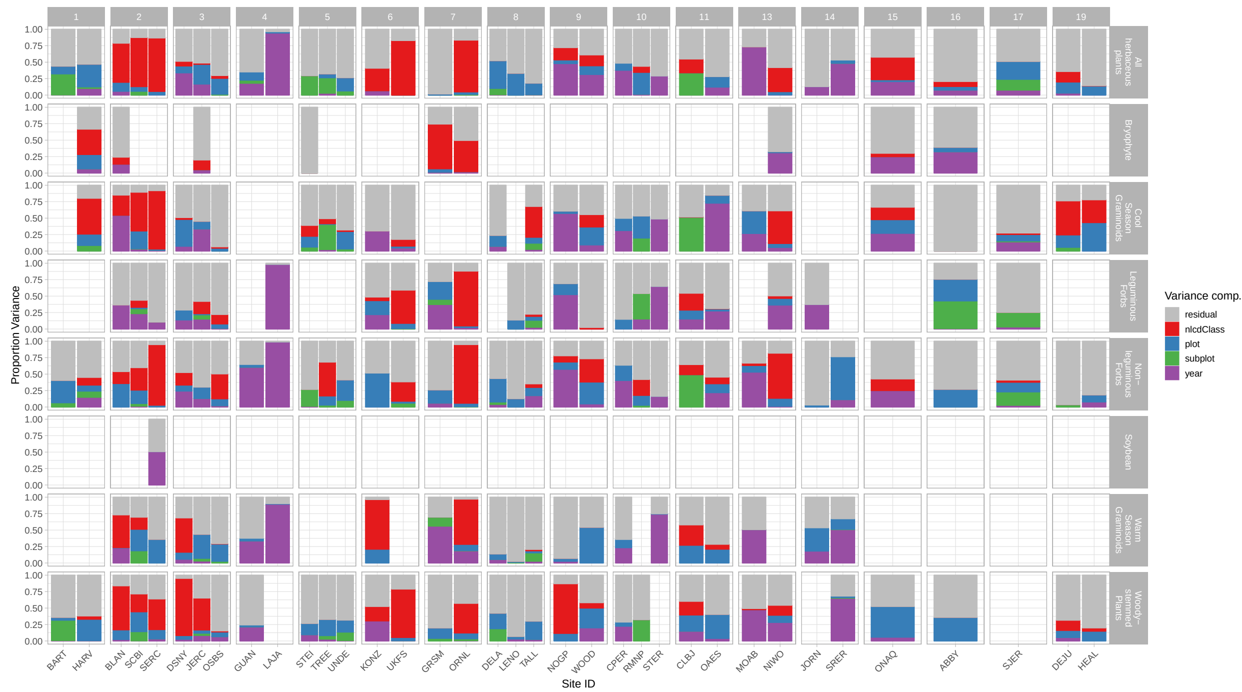

Figure 2: Proportion of the total variance (y-axis) explained by each random factor in the mixed model (colored bars). Panel rows correspond to total or functional group biomass, and panel columns represent sites within domains (x-axis).

3.4 Herbacous biomass power analysis

3.4.1 Response variable, test specifics

The response variable for this test is the effect of `year` on dry mass of each functional group and for all functional groups combined.

3.4.2 Methods

We assessed whether a difference in AGB at peak growing season could be detected across years by fitting the following mixed effect model to the data for each site by functional group combination:

$$Log(standingbiomass + 1) \sim 1 + year + (1|nlcdClass) + (1|plotID : nlcdClass)$$
$$+(1|subplotID : plotID : nlcdClass)$$

We then conducted a power analysis to determine whether a 20% change in peak standing biomass could be detected in consecutive years. We used the parameterized mixed models to simulate 50 replicate data sets for each alternative sampling design at each site with sufficient data. Power for each design scenario was calculated as the proportion of replicate simulations in which we could detect the imposed 20%

change in AGB from year-to-year using a critical value cutoff of t = 2 (approximately $p < 0.05$). For example, a power of 0.80 indicates that 80% of the replicate simulations produced a data set in which a mixed model detected a `year` fixed effect with a p value < 0.05. We used this 80% criterion to identify designs with sufficient power.

3.4.3 Results

An effect of `year` on total AGB could be detected with the current sampling design at 15 sites (HARV, BLAN, DSNY, JERC, GUAN, LAJA, WOOD, CPER, STER, OAES, MOAB, JORN, SRER, ONAQ, and SJER; Figure 3). For these sites, the results show that the current number of plots enabled detection of year-to-year change, but we have not quantified the magnitude of change the design is capable of detecting. At 21 sites there was no significant `year` effect for total AGB, but these results do not differentiate between: a) Year-to-year change occurred but was not detected, b) No year-to-year change occurred, but it would have been detected, or c) No year-to-year change occurred, and a change would not have been been detected had it occurred. Finally, at 7 sites a model could not be fit to the data, and the power analysis could not be performed.

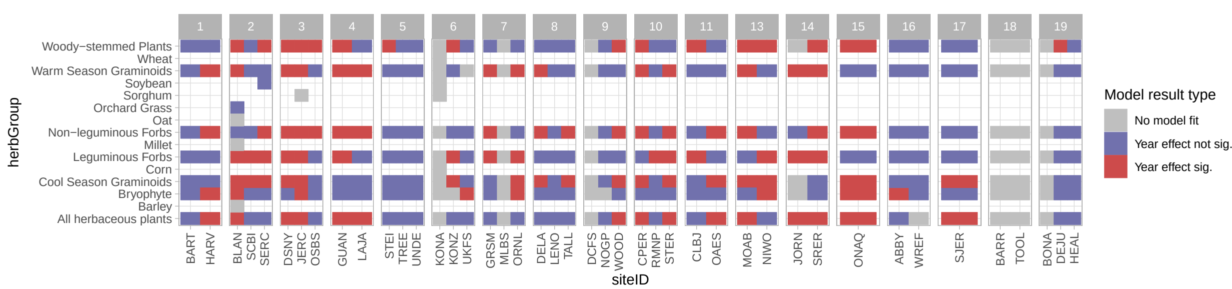

Figure 3: Heat map indicating which site (x-axis) by functional group (y-axis) combinations had sufficient data to fit a linear mixed effects model (above) to predict variation in standing biomass at peak growing season. The 'year' was treated as a fixed effect, and red cells indicate a 'site x functional group' combination for which an effect of 'year' could be detected at a significance level of $p < 0.05$.

To better quantify the ability to detect year-to-year change on a per site basis, we simulated a 20% change in year-to-year total production and performed a power analysis for all sites for which a model could be fit. For this analysis total biomass was analyzed and functional groups were ignored. The power to detect an effect of `year` varied considerably across sites (Figure 4). While retaining the ability to detect a 20% year-to-year change in herbaceous AGB, the power analysis showed that out of 36 sites for which a model could be fit, sampling effort could be reduced to 10 plots at 3 sites (BLAN, MOAB, and SJER), and to 5 plots at 8 sites (SERC, LAJA, KONZ, NOGP, WOOD, CPER, OAES, and HEAL)(Figure 5). Conversely, there were 8 sites (BART, HARV, JERC, TREE, UNDE, ORNL, DELA, and ONAQ) where sampling effort would need to be increased to 40 plots in order to detect a 20% change in standing biomass. Finally, at 6 sites the maximum sampling effort tested (n=40 plots) was insufficient to detect 20% year-to-year change in herbaceous AGB (OSBS, GRSM, LENO, TALL, STER, JORN).

As noted below in the Discussion and Recommendations sections, we have suggested conservative changes to sampling effort at sites with grazing exclosures because the power analysis does not quantify the effect of reduced sampling effort on the ability to detect consumption for each bout.

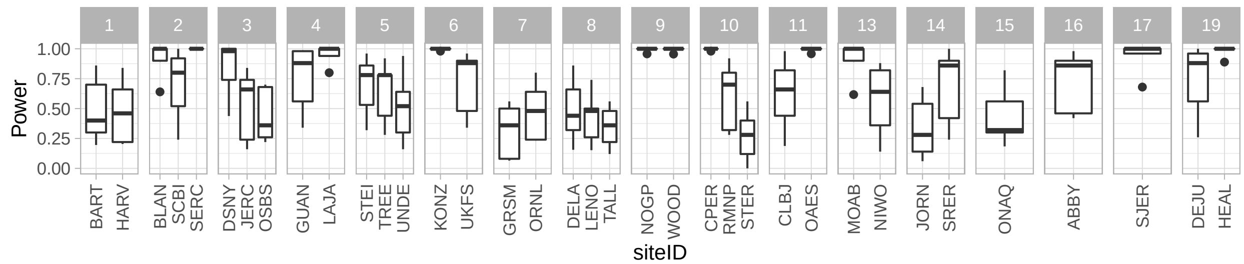

Figure 4: Power to detect a 20% change in total herbaceous AGB at each site across all sampling design scenarios illustrated in Figure 5, using a critical value of $p < 0.05$.

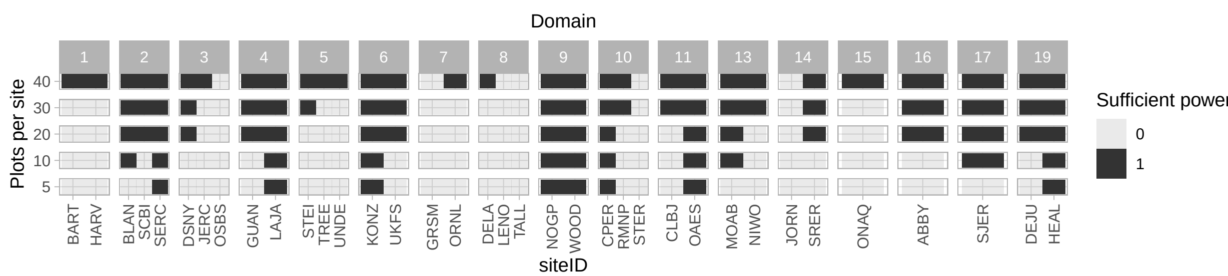

Figure 5: Effect of sampling effort (y-axis) on statistical power to detect a 20% change in total herbaceous AGB across sites (x-axis). Black cells indicate sampling efforts with sufficient power.

4 DISCUSSION

Our hypothesis was that a 4-week sampling interval would allow detection of a significant `exclosure` effect (i.e., consumption due to grazing) in relatively high-productivity sites but not in comparatively low-productivity sites. Contrary to expectations, we found that at the relatively dry CPER and NOGP sites, both with an annual average precipitation of 400 mm or less, it was possible to detect an effect of `exclosure` with a 4-week sampling interval. However, the KONZ site was hypothesized to be a relatively high-productivity site (average of 860 mm of precipitation), and here we detected no effect of `exclosure` with a 4-week sampling interval. Results from other sites generally conformed to expectations. Notably, the very dry MOAB and SJER sites, both with an annual average of 270 mm of precipitation or less, did not have a significant `exclosure` effect. These sites are thus potential candidates for reducing sampling to 1 or 2 bouts per year targeted to phenological biomass peaks, rather than sampling on a regular interval.

The temporal variance component of `year` was dominant in a little over one third of the 36 sites for which we were able to fit models, suggesting that sampling effort could be reduced at some sites without adversely affecting the ability to detect inter-annual change in total herbaceous AGB. Among the spatial components of variance, `NLCD class` and `plot` were the most important, and `subplot` was the least important. However, because the `subplot` variable was important at some sites (Figure 2), we do not propose eliminating within-plot replication at all sites. Rather than impose site-specific sampling designs within plots (i.e., sampling within multiple subplots per plot at some tall-stature sites and not others), we focus instead on optimizing the number of plots sampled per site. We believe that optimizing the number of plots per site will be readily apparent to end-users, while changes to within-plot replication on a per site basis will be more difficult for end-users to parse in terms of data usability.

Power analysis results indicate that reductions in plot number could be implemented at some sites without unduly impacting the ability to detect a 20% year-to-year change in total herbaceous AGB with 80% probability. A related issue not quantitatively addressed in our analyses is that plot reductions acceptable from the perspective of detecting interannual change in peak biomass might nevertheless impact our ability to detect consumption via exclosures at grazed sites. Detailed site-specific recommendations are provided below. To summarize briefly, an examination of the power analysis supplemented by a qualitatively determined minimum of 10 plots per site at grazed sites indicates that out of 36 sites for which a model could be fit:

- Sampling effort could be reduced to 10 plots at 8 sites (BLAN, MOAB, SJER, LAJA, KONZ, NOGP, WOOD, CPER), and to 5 plots at 3 sites (HEAL, SERC, OAES).
- There were 9 sites where sampling effort would need to be increased in order to detect a 20% change in total herbaceous AGB (BART, HARV, JERC, STEI, TREE, UNDE, ORNL, DELA, and ONAQ)
- Sampling greater than 40 plots would be required at 6 sites in order to detect a 20% change in AGB with 80% power (GRSM, JORN, LENO, OSBS, STER, and TALL).

5 RECOMMENDATIONS

5.1 Recommendations applicable to all sites

- We strongly recommend that sampling effort decisions should be made with a minimum of 3 years of data. Recommendations for sites based on 1 or 2 years should be considered more tentative than those based on 3 or more years.
- The variance partitioning results suggest that within-plot replication cannot universally be removed from the sampling design. With that caveat, if site-specific modifications must be made sooner due to changes in budget, site-specific recommendations based on just one or two years of data could be utilized.
- When plot reductions are implemented, the plots that are retained should be spatially balanced and enable unbiased parameter estimates.
- The analyses to identify the minimum sample size (plot number) were based solely on peak biomass. Because power analyses did not account for the ability to detect consumption via exclosures, we recommend retaining at least 10 plots per site at sites with exclosures even if the power analysis based on peak AGB supports reducing plot sampling intensity to 5 plots per site.

5.2 Per site recommendations

Mixed effects model results inform recommended changes to sampling interval at grazed sites; the data theoretically support increasing the sampling interval from four weeks to eight weeks when an `exclosure` effect is weak or not detected (Table 4). Power analysis results indicate that the number of plots sampled can be optimized on a per site basis in order to detect a 20% year-to-year change in total herbaceous AGB (Table 4).

Table 4: Recommendations on minimum number of plots per site, and at grazed sites, the identified sampling interval to be used with portable exclosures.

Domain	Site	Exclosure effect	Optimized sampling interval	Optimized Tower Plot number
D01	BART	NA	NA	inc. to 40*
D01	HARV	NA	NA	inc. to 40*
D02	BLAN	NA	NA	10*
D02	SCBI	NA	NA	20*
D02	SERC	NA	NA	5*
D03	DSNY	NA	NA	20*
D03	JERC	NA	NA	inc. to 40*
D03	OSBS	NA	NA	inc. to > 40*
D04	GUAN	NA	NA	20*
D04	LAJA	0.32 (p<0.0001)	4 weeks	5
D05	STEI	NA	NA	30*
D05	TREE	NA	NA	inc. to 40*
D05	UNDE	NA	NA	inc. to 40*
D06	KONA	NA	NA	model failure
D06	KONZ	0.04 (p=0.41)	8 weeks	5*
D06	UKFS	NA	NA	20*
D07	GRSM	NA	NA	inc. to > 40*
D07	MLBS	NA	NA	inc. to > 40*
D07	ORNL	NA	NA	inc. to 40*
D08	DELA	NA	NA	inc. to 40*
D08	LENO	NA	NA	inc. to > 40
D08	TALL	NA	NA	inc. to > 40*
D09	DCFS	0.47 (p<0.0001)	4 weeks	5*
D09	NOGP	0.16 (p=0.001)	4 weeks	5
D09	WOOD	0.44 (p<0.0001)	4 weeks	5*
D10	CPER	0.07 (p<0.05)	8 weeks	5*
D10	RMNP	NA	NA	30
D10	STER	NA	NA	inc. to > 40*
D11	CLBJ	NA	NA	30

Domain	Site	Exclosure effect	Optimized sampling interval	Optimized Tower Plot number
D11	OAES	NA	NA	5*
D12	YELL	NA	NA	no data
D13	MOAB	-0.06 (p=0.09)	peak bout(s)	10*
D13	NIWO	NA	NA	30*
D14	JORN	NA	NA	inc. to > 40
D14	SRER	-0.13 (p=0.63)	peak bout(s)	inc. to 20*
D15	ONAQ	NA	NA	inc. to 40*
D16	ABBY	NA	NA	inc. to 20
D16	WREF	NA	NA	inc. to > 40*
D17	SJER	0.20 (p<0.0001)	4 weeks	10
D17	SOAP	NA	NA	no data
D17	TEAK	NA	NA	no data
D18	BARR	NA	NA	30*
D18	TOOL	NA	NA	10*
D19	BONA	NA	NA	20*
D19	DEJU	NA	NA	20
D19	HEAL	NA	NA	5*
D20	PUUM	NA	NA	no data

* Sites for which 3 or more years of data were used for the analysis.

Note: In the table above, recommendations for D07 MLBS, D09 DCFS, D16 WREF, D18 BARR and TOOL, and D19 BONA sites were derived from additional analyses run in 2020 when 2 years of data became available for these sites. Figures supporting these analyses are provided in the 'Appendix: Additional Site Results' section.

6 ACKNOWLEDGEMENTS

Thank you to the Plant Biomass and Productivity TWG members for critical assessment of optimization analysis goals and feedback regarding results.

7 REFERENCES

Keller, M., D. S. Schimel, W. W. Hargrove, and F. M. Hoffman. 2008. A continental strategy for the National Ecological Observatory Network. Frontiers in Ecology and the Environment 6:282-284.

8 APPENDIX: ADDITIONAL SITE RESULTS

Data for the D07 MLBS, D09 DCFS, D16 WREF, D18 BARR and TOOL, and D19 BONA sites were pulled from the NEON Data Portal on 2020-05-22, and for all of these sites, addition of 2019 data enabled analysis of 2 years of data per site. Data from the D06 KONA agricultural site were also analyzed but models failed to converge for this site. Data from all sites were analyzed identically to sites analyzed in 2018, and recommendations for these sites are presented in Table 4.

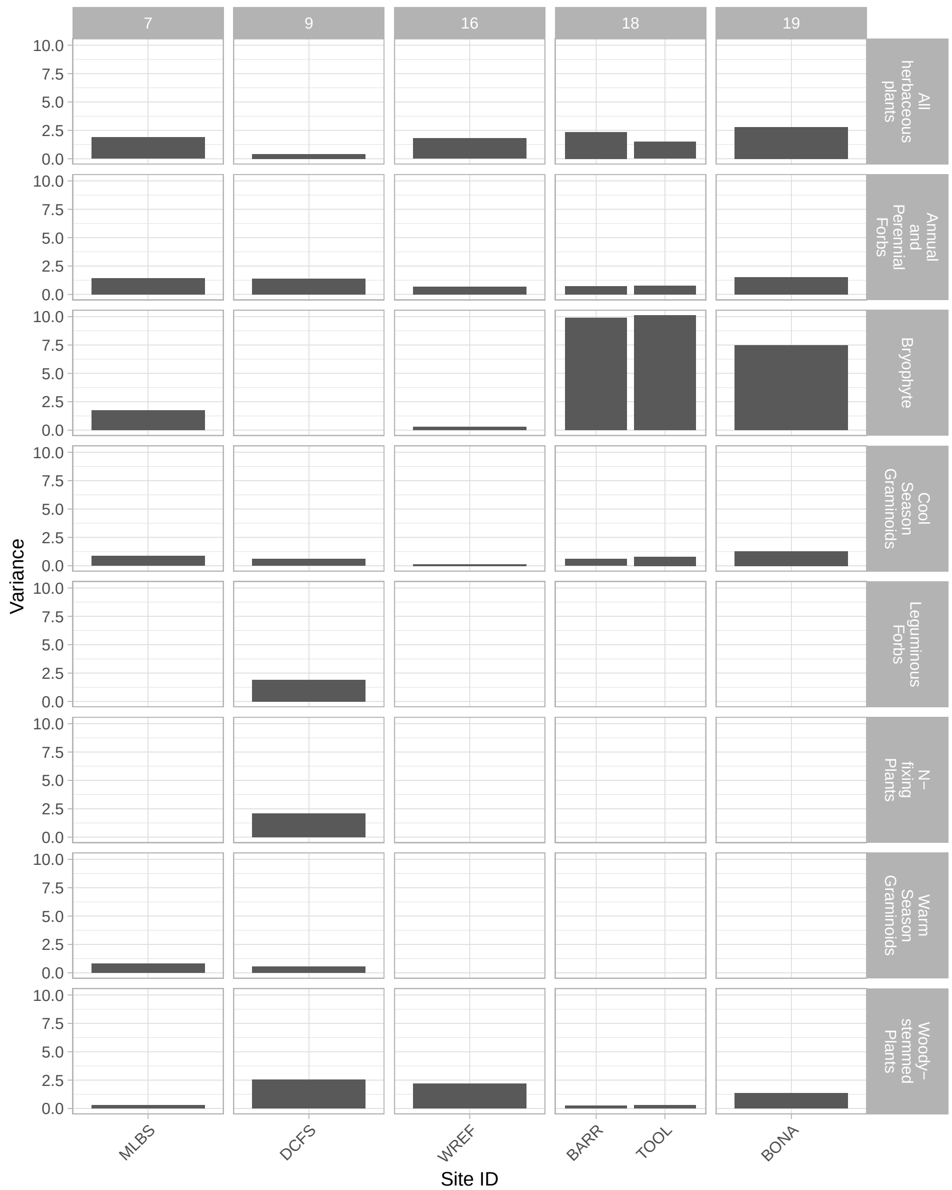

Figure 6: Variance of standing herbaceous AGB at each site for total AGB, as well as for each functional group.

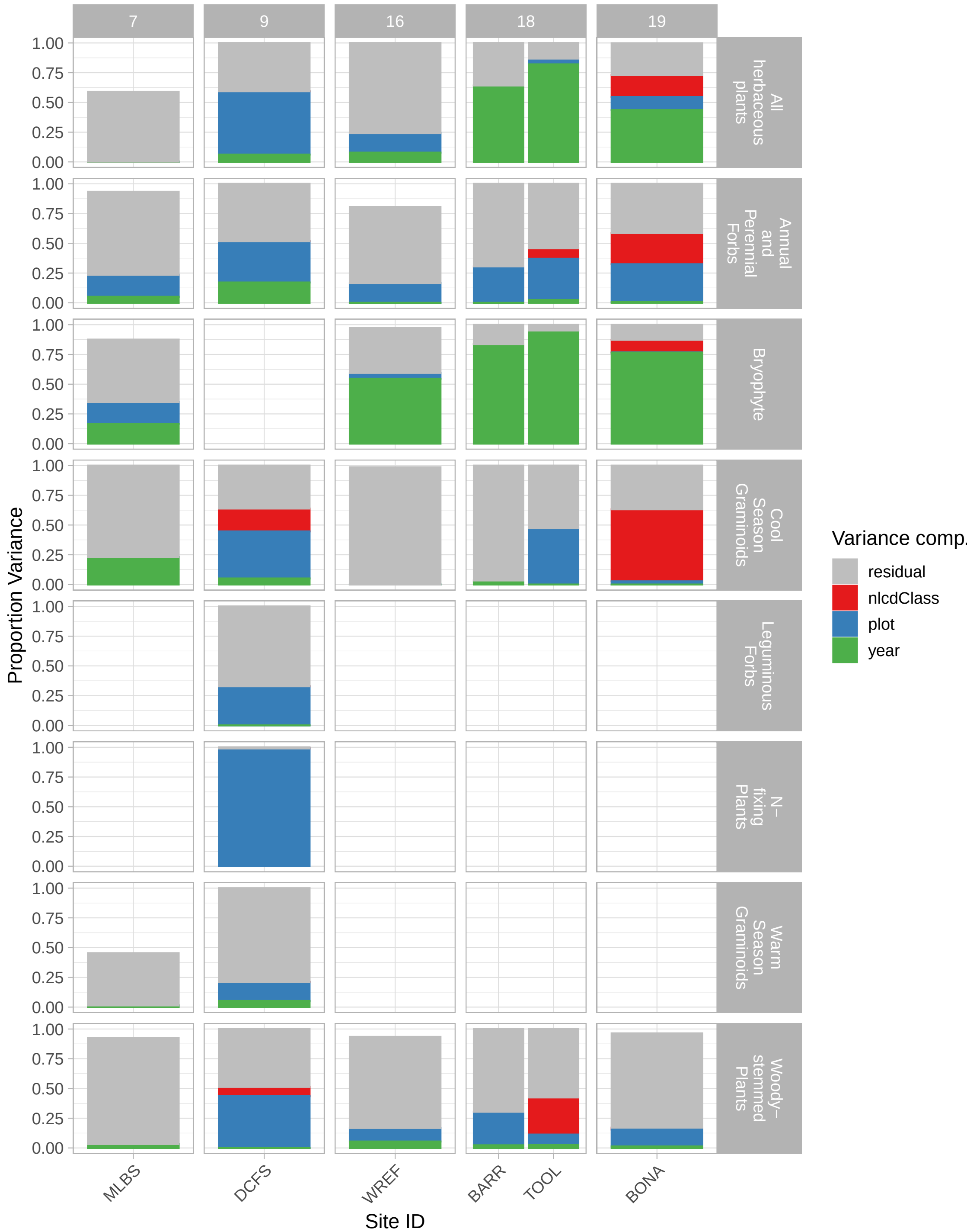

Figure 7: Proportion of the total variance (y-axis) explained by each random factor in the mixed model (colored bars). Panel rows correspond to total or functional group biomass, and panel columns represent sites within domains (x-axis).

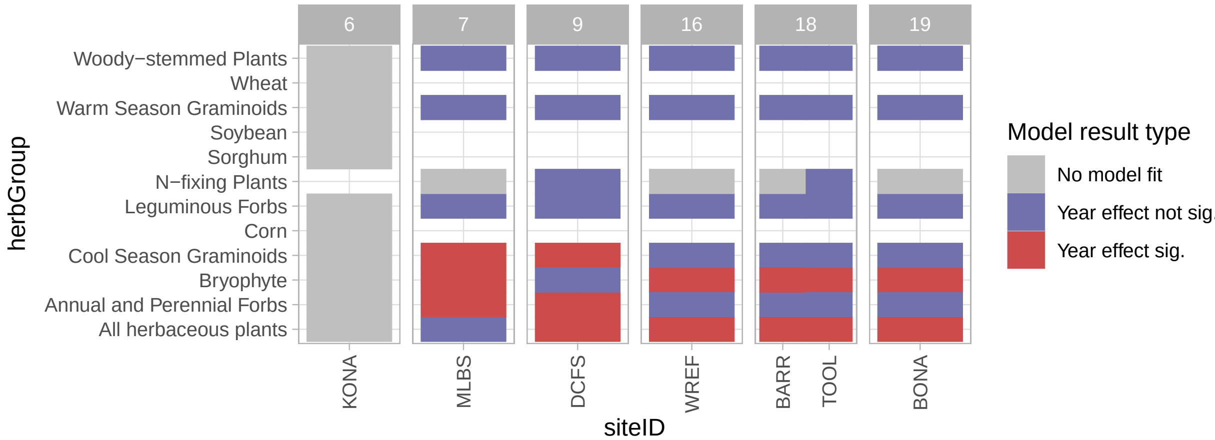

Figure 8: Heat map indicating which site (x-axis) by functional group (y-axis) combinations had sufficient data to fit a linear mixed effects model (above) to predict variation in standing biomass at peak growing season. The 'year' was treated as a fixed effect, and red cells indicate a 'site x functional group' combination for which an effect of 'year' could be detected at a significance level of $p < 0.05$.

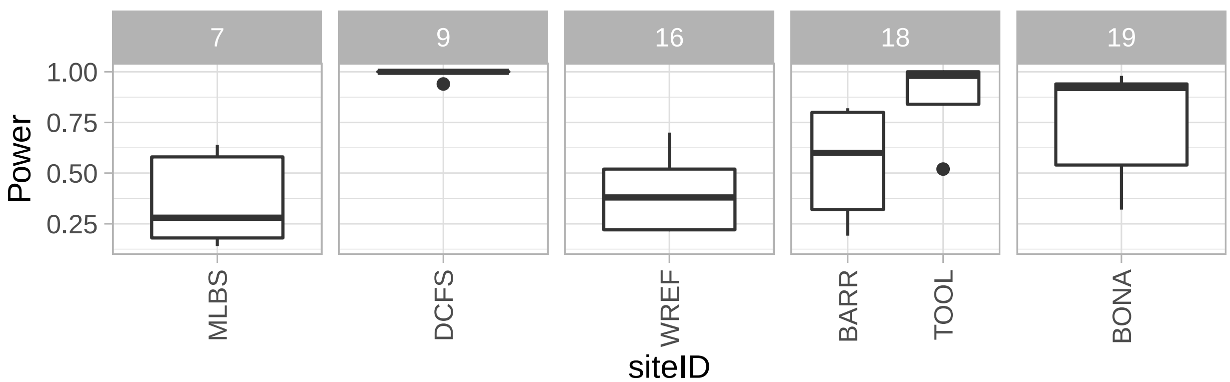

Figure 9: Power to detect a 20% change in total herbaceous AGB at each site across all sampling design scenarios illustrated in Figure 5, using a critical value of $p < 0.05$.

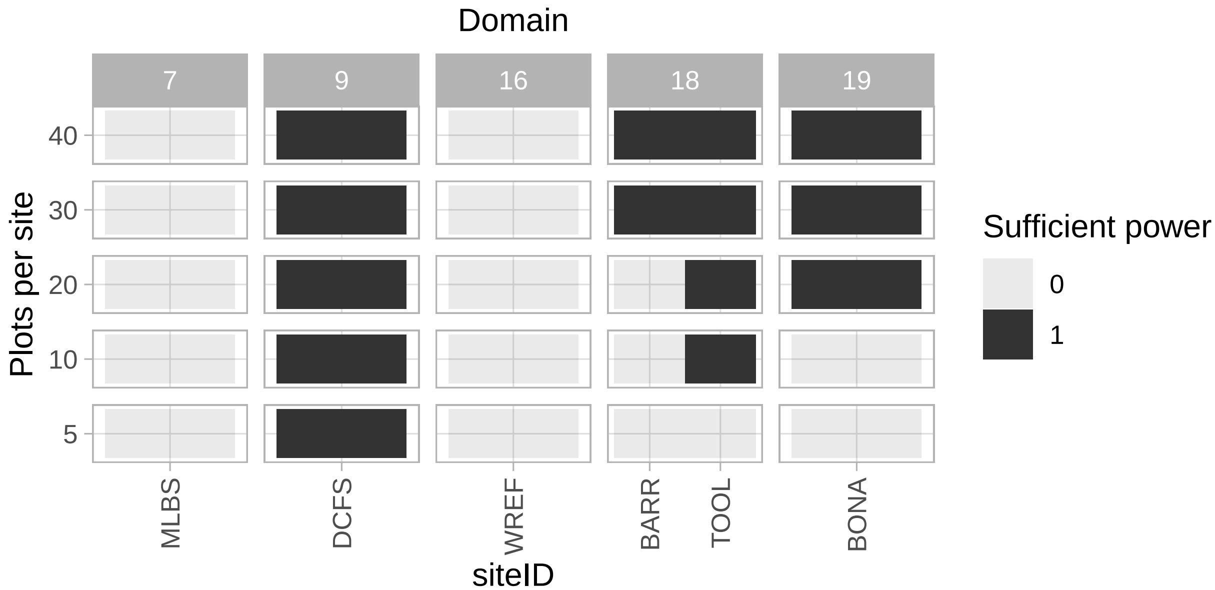

Figure 10: Effect of sampling effort (y-axis) on statistical power to detect a 20% change in total herbaceous AGB across sites (x-axis). Black cells indicate sampling efforts with sufficient power.