

The International Tundra Experiment: An Arctic Monitoring Network

White Paper for the Arctic Observing Summit

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Background and Status

Through the late 1980s, there was growing recognition that the Arctic would be a bell-weather region for climate change, and that effects would likely be earliest and most intense because of the expected amplification of the warming (Maxwell 1992; Moritz et al. 2002; ACIA 2005). In an attempt to predict and monitor the effects of climate change on tundra vegetation, the International Tundra Experiment (ITEX) was founded in December, 1990 at a meeting of tundra ecologists from nine countries hosted by Prof. Patrick Webber at the Kellogg Biological Station of Michigan State University. Participants at the initial ITEX meeting agreed to establish the network according to the principles and actions in a Resolution (Webber and Walker 1991) that was developed during the meeting. The ITEX Resolution laid out the context and the general principles and protocols that would be developed for measurements, coordination, and data sharing and synthesis. Establishing the network by consensus has ensured the longevity of ITEX, which celebrated 20+ years of research and monitoring at University of Texas El Paso in January 2012.

At the initial meeting, it was agreed that a simple, passive warming experiment would be adopted and the focus would be on responses of major circumpolar vascular plant species. The focus on plant responses was due in part to questions from northern residents across the Arctic about the effects of predicted climate change on species used and of interest to them. It was also deemed important to establish the network using relatively simple measurements of phenology, growth and reproduction on populations of important plant species, as this would increase the participation and allow researchers to establish sites with minimal expense.

The warming experiment was to be simple, inexpensive and representative of climate change. These requirements resulted in the use of a passive warming device and the open-top chamber (OTC) was adopted as the experimental apparatus of choice for ITEX (Henry & Molau 1997). The performance of the OTC was evaluated and compared among sites by Marion et al. (1997), and more recently by Bokhorst et al. (2013), and found to increase temperatures in the growing season by an average of 1–3°C over ambient temperatures. The increase in temperature essentially simulates a warm year at each site (Hollister & Webber 2000). While there are some confounding effects with the use of the OTCs (e.g. low wind speed, potential interference with pollination; Marion et al. 1997; Hollister et al. 2006; Bokhorst et al. 2013), the effects of warmer years on tundra plants and ecosystems has been consistent with predictions of experimental warming (Arft et al. 1999; Hollister et al. 2005; Walker et al. 2006; Elmendorf et al. 2012a). While the OTCs continue to be monitored at a number of ITEX sites and provide a rich understanding of the vegetation response to warming, the establishment of each ITEX site as a platform for long-term monitoring and process studies has made the network increasingly more important with emphasis placed on documenting changes in the Arctic.

One of the most important of the founding principles in the ITEX Resolution was the agreement to develop protocols for the exchange of ITEX data among participants that would lead to syntheses of responses across sites. The synthesis of results was greatly facilitated and made relevant by the adoption of protocols for measurements at each ITEX site. Measurement protocols were established

and tested in the early years, discussed and amended at annual meetings, and eventually published in the ITEX Manual (Molau & Mølgaard 1996). ITEX researchers have been at the forefront of sharing data and producing biome-wide syntheses of responses to experimental and observed climate change, and the results are highlighted below.

Sites

Sites in the ITEX network were established in the early 1990s in Arctic and sub-Arctic alpine tundra sites in Canada, Sweden, Greenland, U.S. (Alaska), Norway (mainland and Svalbard), Finland and Iceland. Sites were identified in Russia in the mid 1990s, but funding and other circumstances has prevented research from being established (Henry & Molau 1997).

The number of sites identified as part of ITEX varies depending on the activity and, ultimately, the funding available to each principal investigator. There have been over 30 sites that self-identified as ITEX sites over the past 20 years (see: www.geog.ubc.ca/itex). Figure 1 shows the initial map of 27 sites that was included in a special issue of comparative papers in *Global Change Biology* (1997) and in Arft et al. (1999), and 24 sites in the most recent synthesis of responses to the warming experiments (Elmendorf et al. 2012a). Most of the sites have multiple experiments. In all of these syntheses, researchers were invited by the principal coordinator in ITEX to participate, and included as authors when they agreed to submit data and participate in analysis and/or editing.

Data

The variables measured at ITEX sites varies depending on the investigator and the particular project funding, however, the basic data collected at most sites includes: climate (temperatures, solar radiation, wind speed and direction, etc.); plant phenology, growth and reproduction for major species; composition and abundance of species; soil characteristics (physical and chemical variables, moisture, nutrient availability); and in some sites, net ecosystem production (CO₂ fluxes; e.g. Oberbauer et al. 2007).

Data used in each of the major synthesis papers have been made publicly available; data used in the recent synthesis of vegetation change are available in the Polar Data Catalogue (www.polardata.ca).

Publications

Over 200 publications have resulted from individual ITEX studies (e.g. Hollister et al. 2005; Jónsdóttir et al. 2005; Wahren et al. 2005) and syntheses across sites. The strength of the network has been the ability to compare results from multiple sites using statistical synthesis methods (e.g. meta-analysis, linear mixed models). The first synthesis publications were comparative analyses of responses of species common among sites. These papers (16) were included in a special issue of the journal *Global Change Biology* (e.g. Henry & Molau 1997). This was followed by the first use of meta-analysis to examine plant responses to the warming experiments (Arft et al. 1999). Walker et al. (2006) also used meta-analysis to examine the effects of up to 6 years of warming on species composition and abundance. Elmendorf et al. (2012a) expanded the synthesis in Walker et al. (2006) and included up to 18 years of warming. The responses of tundra vegetation to ambient warming since ca. 1980 was examined by Elmendorf et al. (2012b) using control plots at ITEX sites and additional sites where repeated measurements of vegetation had been made. Monitoring the sites over time using the same protocols and the ability to add new measurements has led to the long-term success of the ITEX network. In addition to the plant and vegetation measurements, net ecosystem production responses to warming were measured at four ITEX sites in the North American Arctic and compared in Oberbauer et al. (2007). Other syntheses are underway (e.g. Oberbauer et al., submitted) or planned.

Results Highlights

Results from ITEX research has been in the forefront of predictions of effects of warming on tundra systems, and in verifying the predictions as the climate warms. One of the main objectives of ITEX was to use a simple warming experiment to determine effects on tundra plants and vegetation that would allow predictions of future change. As described above, the open-top chamber (OTC) was adopted as the passive warming device for ITEX and established in most sites. The warming effect of the OTCs depended on the site and the weather. The maximum warming occurs on clear days with a slight wind, as they allow the air in the OTC to warm without being removed by wind turbulence (Marion et al. 1997; Bokhorst et al. 2013). They are not as effective on calm, overcast days, and the average warming effect has been found to be 1-3° C during the growing season, which is at the low end of predictions from global climate models for Arctic summer temperatures. They experimentally simulate a warm year at the site (Hollister & Webber 2000).

During the early years in ITEX, most researchers followed the detailed protocols for plant phenology and growth, and found that the OTCs caused significant increases in rates of early season phenology and greater growth (Henry & Molau 1997). A meta-analysis of the first four years of phenology and growth data showed that vegetative growth was more strongly increased in the Low Arctic sites than High Arctic sites and herbaceous species had sustained responses, whereas shrub species showed little response (Fig. 1; Arft et al. 1999). These early results indicated that tundra systems would likely become dominated by herbaceous species, although it was known that early responses were generally poor predictors of long-term results (Chapin et al. 1995). Indeed, Sturm et al. (2001) showed that increasing shrub cover had occurred in areas of Low Arctic Alaska over the previous 50 years, and similar results would be reported from other regions (Myers-Smith et al. 2011). The first meta-analysis of vegetation composition and abundance data in the ITEX plots showed that experimental warming increased shrub cover (Fig. 3; Walker et al. 2006), and provided strong evidence that the warming climate was likely responsible for the changes in shrub cover found in many areas of the Low Arctic (Myers-Smith et al. 2011). Using longer-term data, Elmendorf et al. (2012a) found that generally the same responses as Walker et al. (2006), including the loss of lichens and certain bryophyte forms, especially in Low Arctic sites. Therefore, ITEX experimental results predicted an increase in shrub cover, canopy height and the loss of lichen and bryophytes.

These experimental results were also used as confirmation that the increases in productivity and plant cover observed using remote sensing methods (e.g. Bhatt et al. 2010) was due to warming. However, it was the analysis of the changes in species composition, abundance and canopy height in the control plots and other sites with repeated measurements that clearly showed changes in shrub and graminoid cover over the past 30-40 years throughout the tundra biome (Fig. 4; Elmendorf et al. 2012b). The results of the control plot synthesis also showed that while the predictions from the warming experiments were generally true, there were important differences such as: strength of responses tended to be more subtle; greatest changes in shrub cover was in sites that were already warm; and not all groups of bryophytes were negatively affected by ambient warming (Elmendorf et al. 2012b).

Through the coordination and synthesis of spatially distributed experimental studies at ITEX sites we have been able to provide hypothesis based predictions and assessment of vegetation change in tundra ecosystems. ITEX has been a pioneer in what is being called coordinated distributed experiments in ecology, which is a powerful and perhaps necessary collaborative approach to understand and monitor environmental change, and provide results for policy makers (Fraser et al. 2012).

Observing System Design and Coordination

The ITEX sites are found in all Arctic countries (except Russia). The recent synthesis of long-term change in tundra vegetation involved 46 sites; a combination of control plots at ITEX sites and other studies involving repeated measurements of tundra vegetation (Elmendorf et al. 2012b). The experimental design at most sites involved randomly selecting target species and assigning a treatment (warming (OTC) or control). In many sites, the experiments were established in tundra communities along a moisture gradient to capture the variability at the site, and the sample size was between 6 and 20 plots/treatment. Individual plants of major species were then tagged and followed for phenology (both vegetative and reproductive), growth and reproduction throughout the growing season. Specific protocols for measurements of these variables were outlined in the ITEX Manual. Vegetation composition and species abundance was assessed in permanently marked areas within each plot using a standard point-frame method, which involved a standard sized quadrat (e.g. 1 m²) with 100 points. This method was adopted to enable detection of small-scale change in vegetation, but also to reduce observer bias and error and to ensure monitoring could be accomplished by researchers with minimal training.

Measurements of physical variables (temperature, snow depth, thaw depth, light, humidity, soil moisture, nutrient availability) are generally made in a subset of plots in each community type. The ITEX Manual specifies the types of measurements that should be conducted at the plot level, and it is up to individual researchers to determine the level and intensity of these measurements based on their resources. Most sites also have an automated climate station or are close to an official weather station.

The ITEX network is composed of researchers who have chosen to participate and adopt the experimental design and methods; hence, a truly “grass-roots” network. New participants are encouraged to become involved in ITEX through invitations to meetings and through personal contacts with other participants. Each site is maintained by the individual researcher based on the resources they can access, usually through national funding agencies. The network is coordinated by a steering committee, which was originally composed of representatives from each Arctic country involved, a student representative elected by participating graduate students, and led by an elected Chairperson. Currently, ITEX is led by co-Chairs (R Hollister (U.S.A.) and K Klanderud (Norway)) with five other steering committee members from Canada, Iceland, Sweden, U.S.A. and the U.K. The Chairs and steering committee take the lead on organizing meetings and represent ITEX participants on national and international initiatives involving tundra ecosystems.

The major coordinating and exchange event is the ITEX Workshop, which is held annually or biennially and hosted by a participant. The Workshops involve presentations of recent results from sites and discussion of methods, including improvements on existing measurements and proposals for new variables. Discussions of synthesis projects are also held at the Workshops, but the synthesis projects usually involve a separate meeting to coordinate and analyze data and discuss results. The synthesis projects are initiated by a participant after discussions at the ITEX Workshop, who applies for funding from their national agencies. The project is then led by the participant with input from the steering committee, usually coordinated by a post-doctoral fellow, and invitations are sent to other ITEX participants. For example, the most recent synthesis efforts (e.g. Elmendorf et al. 2012a, b) were a result of funding from successful proposals to the International Polar Year programs in Canada and the U.S.A.

Stakeholder perspectives on observing system design and integration

ITEX is a successful program because of the unique combination of a set of relatively simple protocols, experimental design and measurements, and the ability to create synergies from collaboration among participants. Each participant is able to pursue their particular interests in tundra ecosystems and contribute to larger syntheses of results across the tundra biome. Students are a major part of the ITEX success, and are encouraged to attend workshops, synthesis meetings and to visit sites across the network. A special ITEX student travel fund was established by Pat and Mukta Webber at the last Workshop to enable students to travel to meetings in other countries. Another aspect of the success of ITEX is the congeniality among the participants, especially the founders who are now good friends and colleagues. This is evident at the meetings, which are both informative, stimulating and fun. It is this congeniality that allowed ITEX to be among the first large ecological networks to share data freely in order to examine the variability of responses to observed and experimental climate change across the tundra biome.

Mechanisms for coordination of support, implementation and sustaining the ITEX observing system

As mentioned above, ITEX is a “grass-roots” network, which has been successful because of the commitment of individual researchers. Support for the research at each ITEX site is the responsibility of the individual researcher. The success of proposals for research at these sites is undoubtedly aided by the publication of synthesis papers based on the collaboration and data sharing among participants, but is also dependent on the productivity of the individual researcher. In this way, individuals support the objectives in ITEX and receive a tangible benefit for their participation. This approach will continue for ITEX, with the emphasis on monitoring for long-term changes in tundra systems based on the control plots and the establishment of new experiments to examine responses to combinations of factors.

Improvements, relevance and hindrances to the observing network in ITEX

ITEX researchers and sites are already monitoring changes in tundra plants and vegetation in response to observed and experimental changes in climate at the plot level. The ability to combine the plot level data across sites provides the opportunity to examine and compare responses throughout the tundra biome over the past 20+ years. These monitoring efforts in ITEX will continue with dedicated researchers at many sites. The most important obstacle to maintaining a functioning network is the difficulty in funding the basic ITEX measurements over the long-term, and it is these measurements that make the ITEX network so valuable for monitoring change in the Arctic.

While the ITEX data are and will continue to be valuable to assess change in tundra vegetation, improvements to data collections and inclusion of new sites and variables would increase the usefulness of the data for monitoring Arctic change. Below we list some of these potential improvements:

- One of the major missing elements of the ITEX data sets is the lack of sites in the Russian Arctic. It has been a priority in ITEX to bring Russian scientists into the network and several prominent Russian ecologists were involved in the initial phase (Volodja Raszhivin, Nadja Madveyeva, Olga Khitun). However, the Russians sites are remote and the scientists were faced with enormous logistic problems after the collapse of the Soviet Union. We hope that by expanding the opportunities for Arctic monitoring through SAON and the AOS that we can find Russian scientists willing to become participants in ITEX.
- Warming experiments are the main manipulation at ITEX sites which restricts the interpretation of the responses in terms of climate change. While some sites combine changes in snow depth and warming (e.g. Wahren et al. 2005), greater use of multifactor experiments is required,

especially factorial designs of warming + changes in winter and summer precipitation. Results from these experiments will provide better data for ecosystem models that incorporate temperature and precipitation changes.

- Currently, obtaining the data from each plot requires a dedicated field crew, usually graduate and undergraduate students, to be at the study site throughout the growing season. New image analysis techniques and high density digital photographs may allow monitoring of the plots to be maintained in a cost effective manner. Techniques are being tested at the long-term ITEX sites at Alexandra Fiord and at Barrow that show phenological and vegetation changes can be extracted from digital photos. Extracting vegetation indexes such as NDVI, and leaf area from photographs is becoming common place and provides a link between the plot scale and remote sensing studies (e.g. Bhatt et al. 2010). ITEX participants have long been advised to take photographic records of each plot, and adding images to the existing data bases will greatly enhance their usefulness for monitoring.
- Biological interactions are also relatively unstudied at ITEX sites. For example, the effects of herbivores has been shown to be important in these systems (Henry 1998) and may result in responses that oppose typical responses to warming (Post & Pedersen 2008) in tundra systems. In addition, effects on pollinators and pollination are poorly studied despite obvious importance. Discussions at ITEX Workshops always include these interactions, and some new studies are underway or proposed. For example, factorial experiment combining warming (OTCs) and different levels of goose grazing intensity was run for three years in Svalbard within the EU funded FRAGILE project and further demonstrated complex interactions between warming and grazing intensities in terms of individual plant responses, plant community composition (Jónsdóttir et al. in prep.) and invertebrate herbivory (Gillespie et al. in prep.). We encourage further development of monitoring plans that address trophic interactions in combination with warming experiments.
- Adaptation and migration are the two options for organisms in the face of rapid climate change. The ITEX studies provide examples of how local populations of wide-spread species respond to warming (and other factors in a few sites), but the ability of more southerly populations to adapt to currently northern areas is unknown. Establishing studies that use common gardens and field experiments to test for local adaptation to environmental change should be another priority for ITEX researchers.
- Soil processes are important drivers of change in terrestrial systems, and how they react to climate change will impact responses in tundra systems. While measurements of soil moisture and nutrient availability are generally included at most ITEX sites, assessments of important processes in the soils (e.g. decomposition, mineralization, nitrogen fixation, microbial diversity) are not common. How soil processes may change with warming and changes in precipitation would enhance our predictions of responses in tundra systems.
- Energy and mass exchanges between tundra systems and the atmosphere are important pathways for feedbacks that link responses in the tundra to regional and ultimately, global climate (e.g. Chapin et al. 2005). Some ITEX sites have conducted measurements of CO₂ fluxes using chamber methods to assess net ecosystem production (NEP) in the treatments (e.g. Oberbauer et al. 2007). The methods for measuring NEP are now relatively easy and inexpensive, and including them in a monitoring framework at ITEX sites would give much needed information on variability of these fluxes over space and time.
- Maintaining the monitoring network would be enhanced by including sites in national and regional parks where monitoring can be incorporated into the operations. In addition, establishing sites near northern communities would allow monitoring to be part of school

science classes. This is being accomplished in northern Canada where high school students measure berry production in plots established with the help of community members.

The observations made at ITEX sites over the past 20+ years are shared through the many publications and presentations made by ITEX researchers. Information is also available through the ITEX web site (www.geog.ubc.ca/itex). With the vegetation composition and abundance data from warming and control plots in 46 sites now available through the Polar Data Catalogue, other scientists can use the data in their studies, and hence add value to the ITEX data. This aspect of ITEX research will continue and be enhanced with inclusion of all data collected over the past 20+ years. Hence, the observations are likely being shared optimally among all stakeholders at the present time. However, increasing the ability to make the results more accessible to northern residents in all countries through non-scientific outlets should be improved. This has been a goal in ITEX for a number of years, which will be aided by the same objective in SAON and other pan-Arctic observing systems.

ITEX has been fortunate in the lack of hindrances to collection and sharing of data for the most part. Like most scientists, ITEX researchers are willing to share data and participate in large synthesis efforts, as long as their efforts are acknowledged. In ITEX, this is usually by being included as an author on synthesis reports. Access to sites is difficult in very remote areas with the rising costs of logistics. This is clearly one of the reasons for the lack of sites in the Russian Arctic over the past 20+ years.

Summary

ITEX is a successful network of coordinated distributed experiments throughout the Arctic tundra that has contributed to the monitoring of change in the circumpolar region and beyond for over 20 years. The long-term success of the network has been a combination of clear planning at the outset, standardized methods and experimental designs, dedicated and inspired researchers, and a willingness and desire to share information to gain new insights on the structural and functional responses of tundra systems to climate change. The collaborative approaches to research and monitoring in ITEX and the experience gained through long-term studies will help to ensure ITEX researchers continue to make important contributions to observe, record and understand the changes in the Arctic.

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Figure captions

Figure 1. A) Map of 27 original ITEX sites from Arft et al. (1999) and B) map of 24 ITEX sites included in the synthesis of vegetation change in warming experiments across the tundra biome in Elmendorf et al. (2012a).

Figure 2. Effect size (d index) of experimental warming over a 4-yr period for vegetative growth at ITEX sites. The mean effect size for each treatment year is indicated with a diamond and vertical bars representing the 95% CI. In the top row (A), all studies are included in the analysis. Studies are then categorized by (B) geographic zone (high arctic, low arctic, and alpine) and (C) broad functional types (woody and herbaceous). An asterisk (*) indicates that the effect is significantly different from zero at $P \leq 0.05$. From Arft et al. (1999).

Figure 3. Response of tundra plant community variables to experimental warming at ITEX sites. The values represent the mean effect size and 95% confidence interval from meta-analyses of the 22 variables measured in all studies, where studies consisted of the site and each of the growing seasons in which measurements were made. Effect sizes for cover were in the range considered small by meta-analysis convention, indicating a small magnitude of response. Moderate effect sizes were found for canopy height, ordination scores, and diversity indices, indicating a larger magnitude of response. Note that only the magnitude is important for the ordination scores. Modified from Walker et al. (2006).

Figure 4. Biome-wide changes in vegetation height (**a**) and abundance (**b**) of each vegetation response group. Vegetation height is expressed as the plot canopy mean and the maximum of each taxon and abundance is expressed as the probability of increase. Error bars show ± 2 s.e.m. based on intercept-only GEEs and are emboldened where mean change rates were significant at $P < 0.05$ using Wald tests. Sample sizes (number of studies, number of locations) and response groups are indicated on the x axis. From Elmendorf et al. (2012b).

Figures

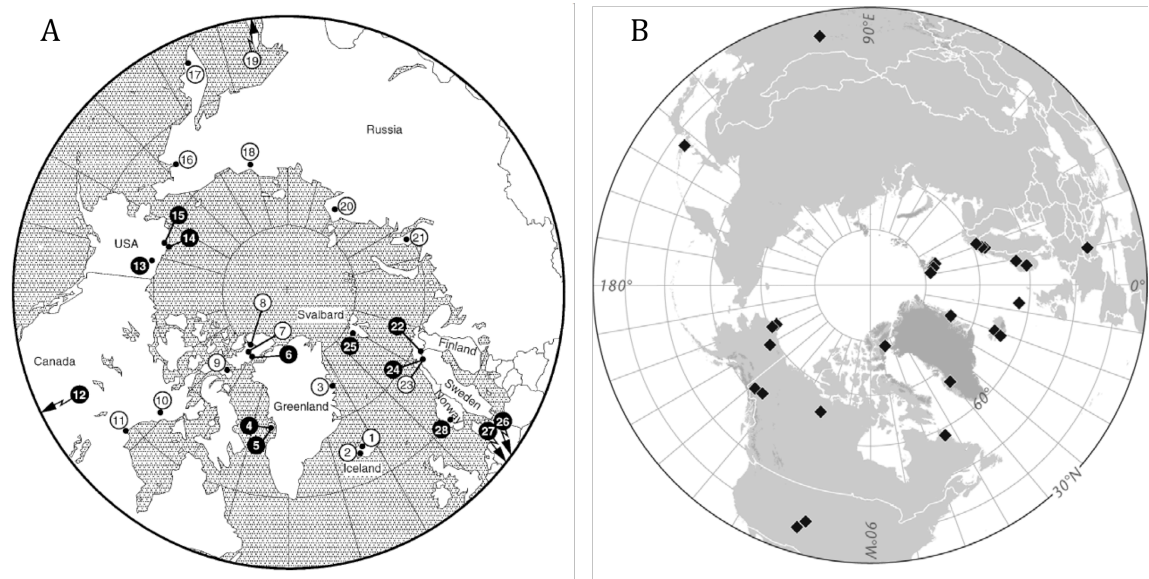


Figure 1.

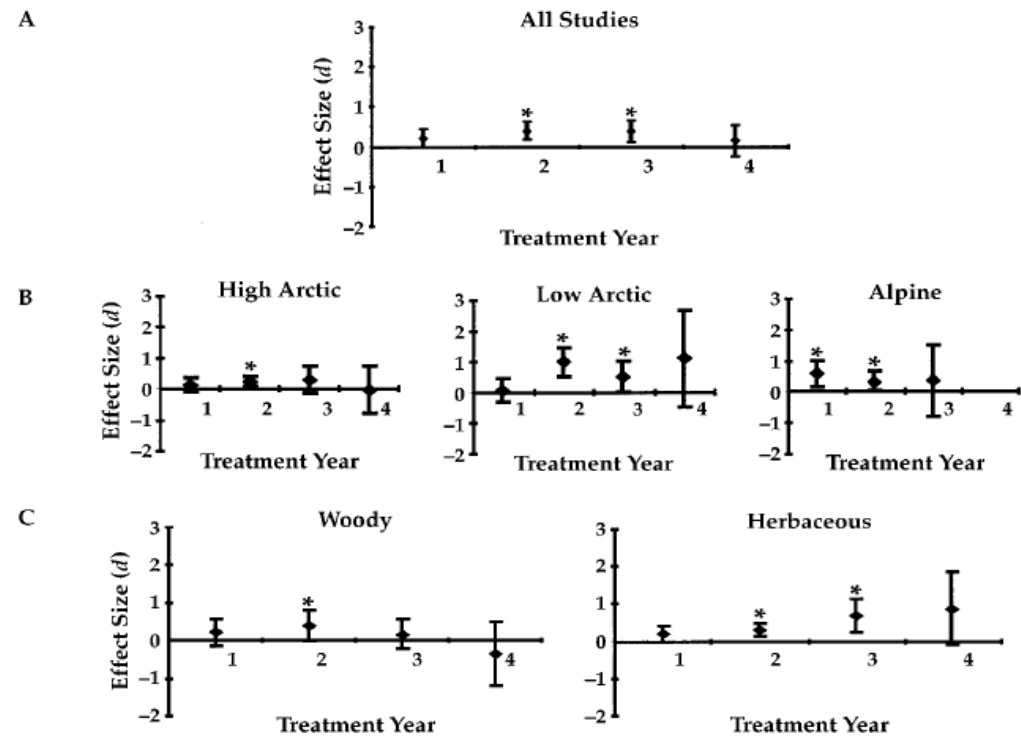


Figure 2.

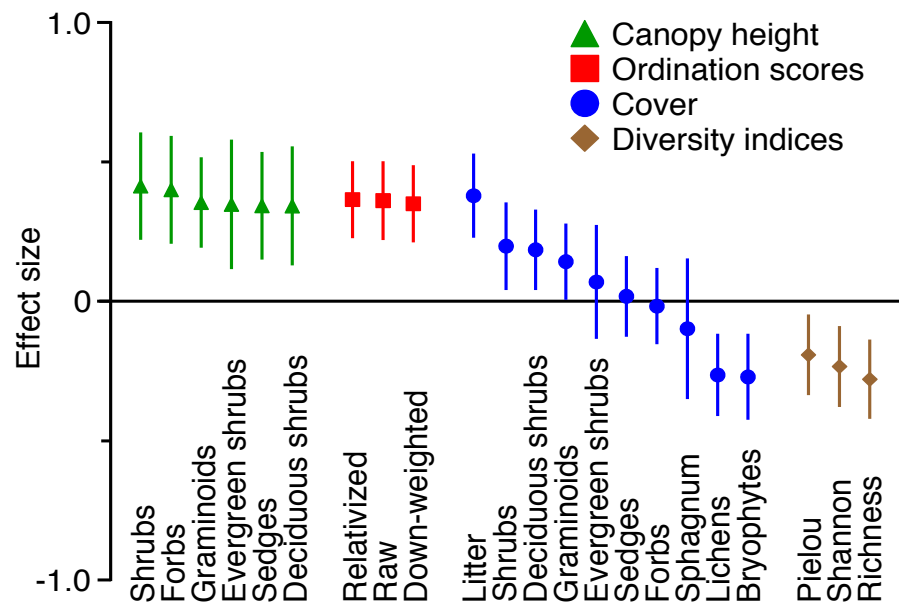


Figure 3.

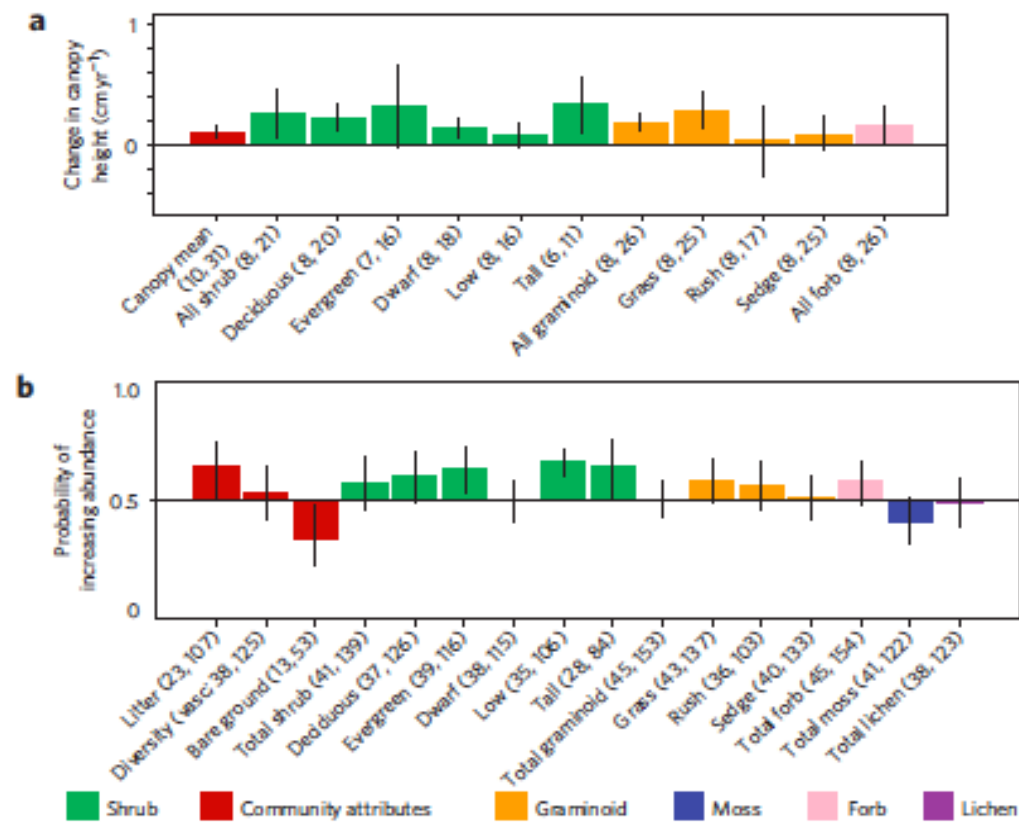


Figure 4.