A White Paper on *Phenology across LTER*

Introduction

Phenology is, in the words of Aldo Leopold, a "horizontal science" that cuts across and binds together multiple biological disciplines (Leopold and Jones 1947). It is a far-reaching but poorly understood aspect of the environmental sciences. Phenological research has been a component of LTER at several sites over the years. However, it has not received the attention or resources to bring it to the forefront as an effective theme for interdisciplinary and cross-site synthesis.

With the establishment of the USA National Phenology Network (USA-NPN), it is an appropriate juncture to assess the status of phenological knowledge across the LTER Network and to consider how the LTER Network might beneficially interact with the USA-NPN.

At the 2006 LTER All Scientists Meeting a working group was convened on phenology. The session was well attended with 10 LTER sites, LNO, and CERN represented. One of the recommendations sent forward was the need for a follow-on workshop to evaluate the status of LTER phenological research, to build a community of interest that could facilitate phenological analysis and synthesis across the LTER Network, and to commence a cross-site synthesis of some extant phenological data.

A workshop was funded by LNO and occurred February 26-March 2 2007 at the Sevilleta Field Station. From this workshop emerged three main products: (1) inventory of LTER phenology datasets (Appendix A); (2) establishment of a website to facilitate information interchange (http://globalmonitoring.sdstate.edu/LTER-phenology/); and (3) this white paper.

We begin by presenting some useful definitions and distinctions regarding phenology and proceed to describe the results of our inventory of LTER data. We present a preliminary but revealing analysis of meteorological data at the sites represented at the workshop. We conclude with recommendations about next steps to move forward the study of phenology across LTER.

Definitions and Distinctions

There are several definitions of phenology in circulation. We have found the following statement, first articulated by the US/IBP Phenology Committee to be particularly concise and insightful:

> Phenology is the study of the timing of recurring biological events, the causes of their timing, their relationship to biotic and abiotic forces, and the inter-relations among phases of the same or different species. (as cited in Lieth 1974, p. 4).

It is important to make the distinction between *phenology* and *seasonality*. Seasonality refers to temporal patterns of abiotic variables occurring at annual or sub-annual timescales. Phenology and seasonality are complementary aspects of ecosystem function that interact. The onset of the temperate spring provides a canonical example of that interaction. Air temperatures rise due to increasing insolation which triggers soil thawing. Leaf out of tree canopies results in a flush of moisture into the atmospheric boundary layer moderating diel temperature ranges (Schwartz 1996) and increasing convective cloud cover (Freedman *et al.* 2001).

While phenology studies abound in the temperate zones often with a focus on temperature as the driving forces, studies in tropical phenology show that the attenuated climatic forcing enables the expression of diverse phenological patterns that nonetheless exhibit the influence of the seasonality of dry periods, the seasonality of irradiance patterns, and plant-animal interactions (Ewusie 1992; van Schaik *et al.* 1993; Zimmerman *et al.* 2007).

The influences of climate modes and atmospheric teleconnections on phenology is well recognized at some locations, but there is significant further work needed to untangle climatic variability, directional climatic change, and anthropogenic modification of the land surface (White *et al.* 2002; Greenland *et al.* 2003).

Land surface phenology is defined as the seasonal pattern of variation in vegetated land surfaces observed from remote sensing (de Beurs and Henebry 2004; Friedl *et al.* 2006; Morisette *et al.* 2008). Land surface phenology is distinct from plant phenology because sensors record a mixture of signals from many species as well as abiotic sources such as snow, soils, water, and anthropogenic surfaces. Spatially extensive coverage of remotely-sensed observations provides an important source of data for phenological study, especially for the development of ecological forecasts in conjunction with ground level observations of species phenologies.

Phenology also encompasses the recurrent appearance and disappearance of vertebrate and invertebrate species, life cycle patterns, temporal sequences of population dynamics, reproductive behaviors, and species abundances and interactions, both in terrestrial and aquatic environments.

Phenology Data across LTER

We searched for phenology data at the website of each LTER site as well as through the LNO data catalog. We were able to identify phenologically explicit datasets at 18 of 26 LTER sites, some are ongoing and some are of short or indeterminate duration. These datasets constitute a relatively minor proportion of ongoing LTER data collection. The dearth of publications on these datasets suggests a fresh opportunity for analysis and synthesis.

There are many more datasets that are phenologically implicit. In other words, these datasets offer, due to the kinds of phenomena measured and the tempo of measurements, possibilities for phenological analysis. An example of a pheno-implicit dataset collected across many LTER sites is litterfall. Meteorological data are abundant at LTER sites and provide context for phenological analyses. Appendix A provides a table of LTER datasets by site that we were able to identify as phenologically explicit and phenologically implicit.

The time is ripe for a concerted synthetic effort. Phenology can serve as an integrative theme for network-scale synthesis within the conceptual schema set forth in the recent planning grant efforts. Phenology provides a basis through which to distinguish change from variability and to explore the ecological consequences of changing environmental conditions.

The challenge and opportunity of phenological analysis

There are many ways to collect and to analyze phenological data. At present, there is little or no standardization on data collection, especially across taxa and biomes. Data are gathered across a variety of temporal frequencies, spatial extents, and measurement scales and datasets are of variable duration. These characteristics present a challenge for cross-site synthesis.

As a first attempt to compare climatic and meteorological influences on phenology across sites, we developed a graphical representation of seasonal progression of meteorological variables by plotting the accumulated growing degree-days (AGDD calculated from 01JAN using a base of 0 ^{o}C) on the abscissa against the accumulated daily precipitation (APPT calculated from 01JAN in mm) on the ordinate. These graphs (see Appendix B) provide a possible means to identify phenological drivers across a wide array of ecosystems represented by LTER sites. Some patterns evident in these graphs include:

- Interannual variability in precipitation at NWT is greater in the warm season than in the cool season;
- Almost all of the precipitation at HJA occurs during the cool season;
- A distinct bimodality in wetter versus drier springs at HRF with a pattern of many small precipitation events during the warm season;
- Suggestion of a trimodality in precipitation patterns at KNZ around AGDD=2000 that mixes after AGDD=3000 and by the end of the year appears as a bimodal pattern; Onset of warm season precipitation at both SEV and JRN exhibits high interannual variability with evidence of trimodality at SEV and bimodality at JRN; and
- Relatively low seasonality in daily precipitation arrival rate at LUQ, but high interannual variability; and
- Interannual variability of APPT and AGDD grasslands and woodlands scale differently (Figure 1).

Approaching comparative phenology from the viewpoint of common meteorological variables, we provide a context for identifying phenological patterns across biomes and linkages to climate modes.

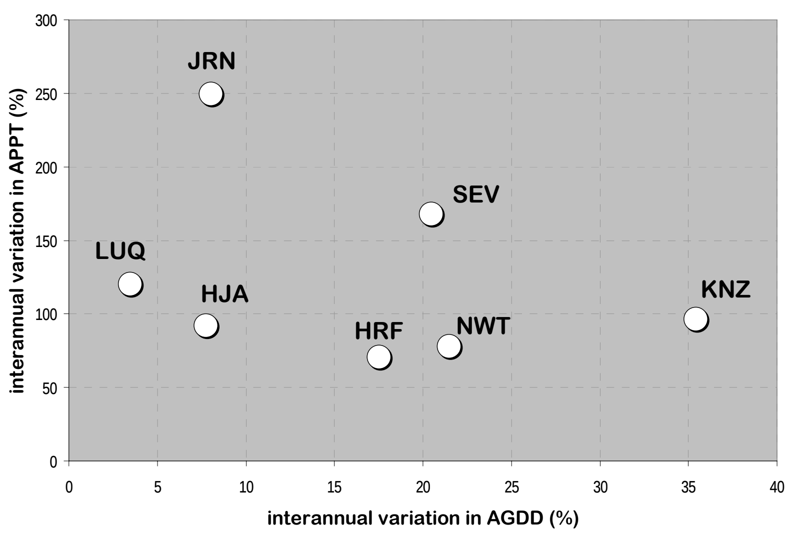

Figure 1: Interannual variability of climatic envelopes 1997-2006 at selected LTER sites as measured by the range as a percentage of the minimum final annual value. The grasslands sites appear to exhibit different scaling relationship from the woodland sites.

Recommendations

On the basis of our deliberations, we recommend the following steps to advance the integrative use of phenological data within sites, across sites, and beyond sites:

- That the LTER network dedicate an annual LTER science meeting in the near future on the topic of phenology, including analytical methods and cross-site observational protocols, which may lead to the production of an LTER synthesis volume;
- That the LTER network endorse a proposal to NCEAS to convene a working group to identify, mine, analyze, and synthesize extant phenological data from diverse sources and to discuss approaches to bring under a common conceptual framework observations of plant and animal phenologies from terrestrial and aquatic environments across diverse biomes; and
- That the LTER network actively engage the USA-NPN at all LTER sites, with an emphasis on science in addition to environmental education.

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Appendix A: Phenology Datasets across the LTER Network

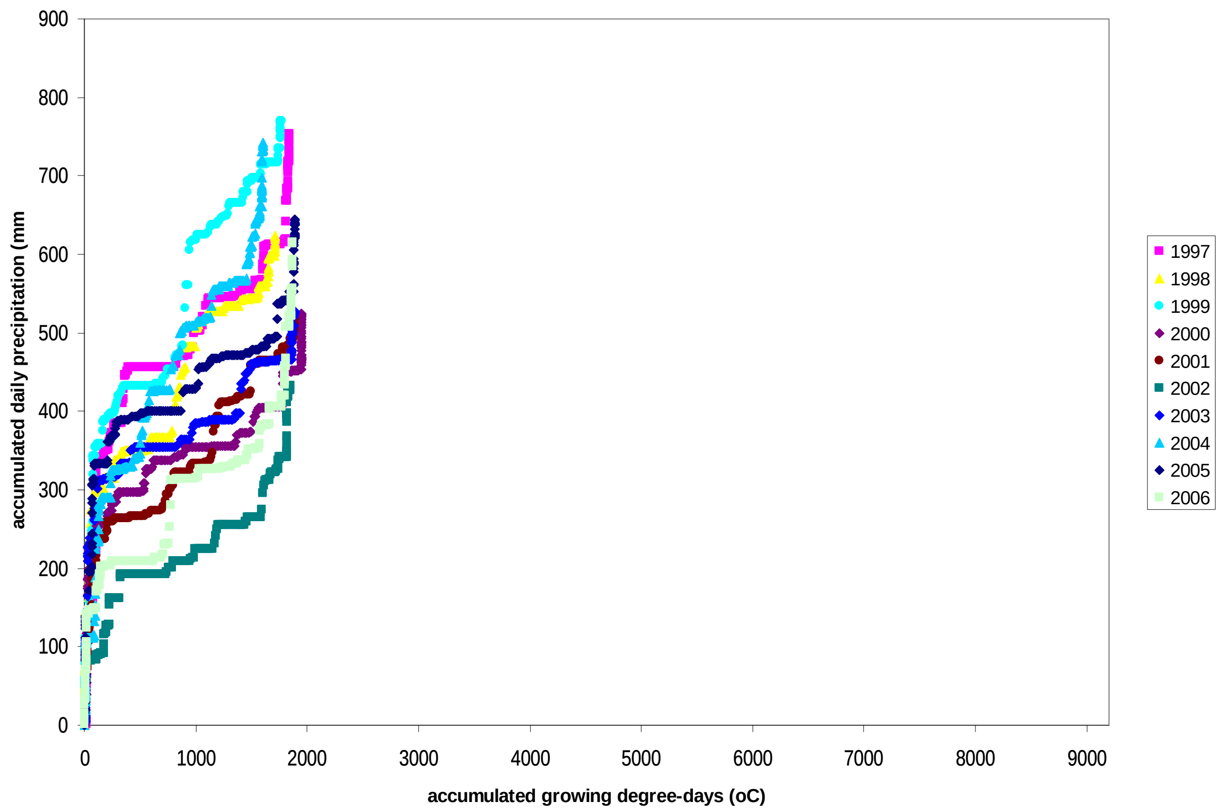
Site	Phenologically-Explicit Datasets	Phenologically-Implicit Datasets
AND	Plant phenology dataset; Caterpillars on shrubs; Nighttime moths; butterfly transects; seasonal soil respiration; fish phenology	spotted owl life history; stream ecology; streamflow; stream chemistry; NPP; permanent study plots; sapflow data; cone production; litterfall; fine woody debris inventory
ARC	SAR backscatter; sedges; evergreen; deciduous plants; *Eriophorum* flowering; flowering abundance latitudinal transect	lake water quality; plankton; inlet discharge; fish; streamflow; stream temperature; stream water quality; aquatic insects; biomass production & chemistry; soil nutrients; thaw depth; trace gas emissions; precipitation chemistry
BES	?	Streamflow; stream chemistry
BNZ	?	Defoliating insects; river discharge; litterfall; hare pellets; morel productivity; soil respiration; ice break-up; vegetation cover; soil solution chemistry
CAP	Plant phenology	Leaf chlorophyll content
CCE	?	Hydrographic cruise data
CDR	Insect phenology; SLTER grass phenology; plants of CDR	Experiments
CWT	Inter and intra annual variation in belowground carbon pools	Litterfall; hydrological datasets
FCE	?	water quality; mangrove litterfall; algal and bacterial biomass; fish community dynamics
GCE	Flowering dates	Grasshopper surveys; phytoplankton productivity
HBR	Tree phenology; phytophagous insects; caterpillar abundance	litterfall; bird population and abundance; biomass; LAI; fine root biomass; streamflow; stream chemistry; lake chemistry; tree growth increments
HFR	woody species; soil warming experiment; lilacs	eddy flux datastreams; streamflow; litterfall; woody increment dendrometer; soil respiration; soil respiration with rainfall exclusion;
JRN	Phenology transects associated with NPP plots	Lizard pitfall data; small mammal trapping; leaf litter; cryptogamic cover; rabbit pellets; soil surface disturbance; termite casings; wetfall vs dryfall precipitation; arthropod pitfall; annual photo series of NPP sites; creosote & mesquite litterfall
KBS	baseline spatial variability study	Littertrap biomass; Ameriflux tower; soil

		invertebrate survey; insect abundance; soil leachate
KNZ	plants (LTER); plants (KEEP); birds (LTER); animals (KEEP)	biweekly ANPP; gallery forest litterfall; plant reproductive effort; streamflow; irrigation transect; belowground plots
LUQ	Tabonuco woody species; fern sporophyte growth	Litterfall; shrimp; streamflow; stream chemistry; soil respiration; soil solution chemistry; soil nutrients; soil microbes; arthropod abundance; herbivory; snails
MCM	?	streamflow; stream chemistry; snow depth and glacier stake heights; nematode abundance in experiment treatments; bacterial production; [Chl A]; phytoplankton density and production
MCR	?	?
NTL	lake ice seasonality	Physical limnology; chemical limnology; high resolution DO sensor; groundwater levels; bacterial and plankton respiration; microbial activity
NWT	individual plants in nodal plots; N & P fertilization; ITEX warming study	snow fence experiment; alpine lake ice thickness; NADP measurements; stream chemistry; streamflow; snowpack ablation; snowpack depths; soil trace gas emissions
PAL	Adelaide penguin breeding success and chronology; krill surveys	physical oceanography; marine carbon cycling; zooplankton surveys; bioacoustic monitoring; bird surveys
PIE	macrofauna sampling; breeding bird surveys; salt marsh bird surveys; volunteer bird surveys;	salinity; nutrient loading; sedimentation; water quality; water discharge; water table height; phytoplankton community in water column; benthic sampling; fertilization experiments
SBC	?	Stream chemistry; ocean current characteristics and biogeochemistry; streamflow; kelp forest community structure and dynamics; fish abundance; benthic invertebrates and understory algae; abundance and size of giant kelp; historical kelp aerial surveys

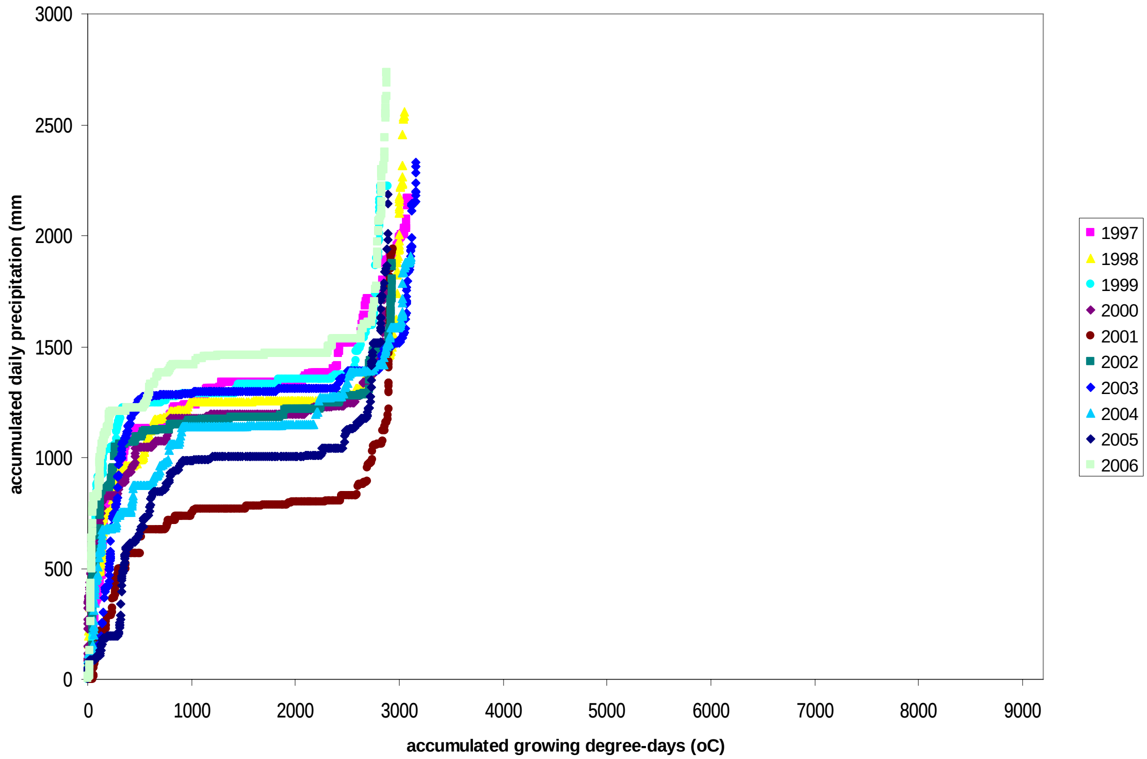
SEV	core site plants; transect plants	Bees; grasshoppers; ground-dwelling arthropods; seed germination from NPP data; litterfall; rodent reproductive status; lizard reproductive status; plot level photography; bird survey; oak, piñon, & juniper masting data
SGS	long term study; grasses; forbs; shrubs;	arthropod pitfall sampling; rodent trapping; lagomorph road & nighttime surveys; small mammal trapping; carnivore scat count; vegetation density and cover; aboveground litter decomp; soil biogeochemistry; 13-lined ground squirrel; BBS; avian species road counts; ANPP; plant C:N & lignin
VCR	?	Spartina alterniflora biomass; small mammal surveys; litter biogeochemistry; water chemistry

Appendix B: Climatic Envelopes (1997-2006) at Select LTER Sites: NWT, HJA, HRF, LUQ, KNZ, SEV, and JRN. In each graph the abscissa shows accumulated growing degree-days (base 0 °C) and the ordinate displays accumulated daily precipitation (mm). Scaling of axes is inconsistent in the ordinate, but consistent in the abscissa.

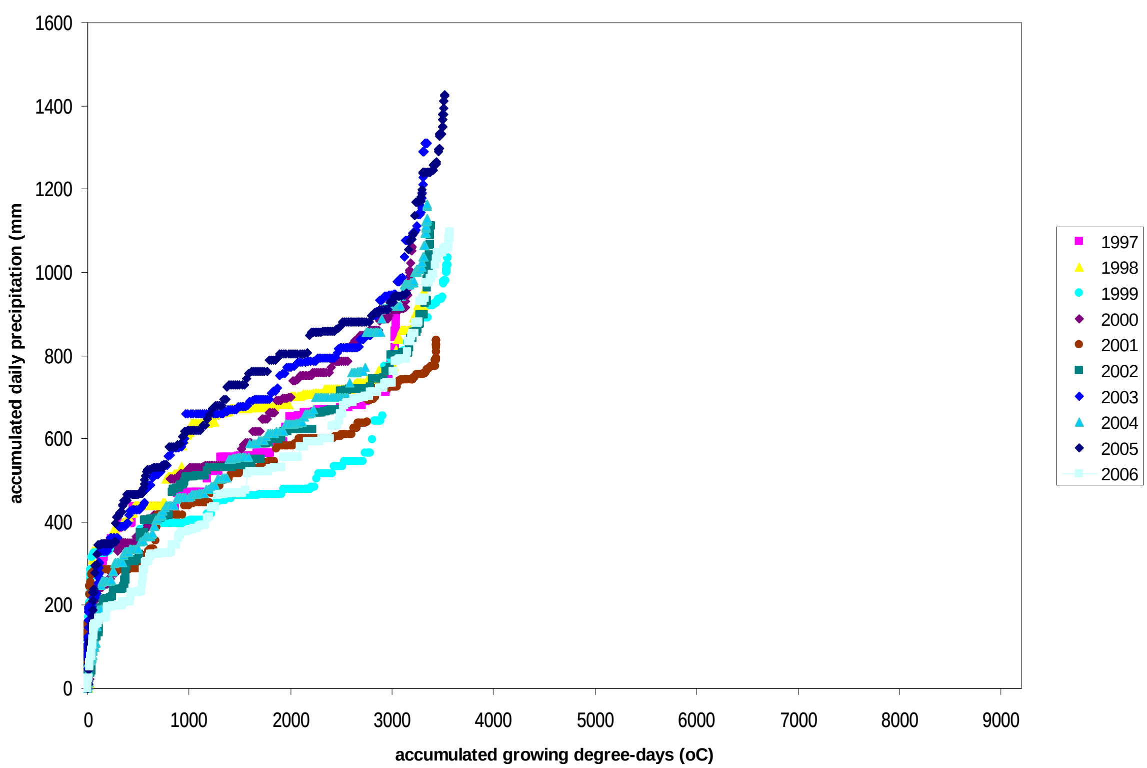
B.1. NIWOT RIDGE



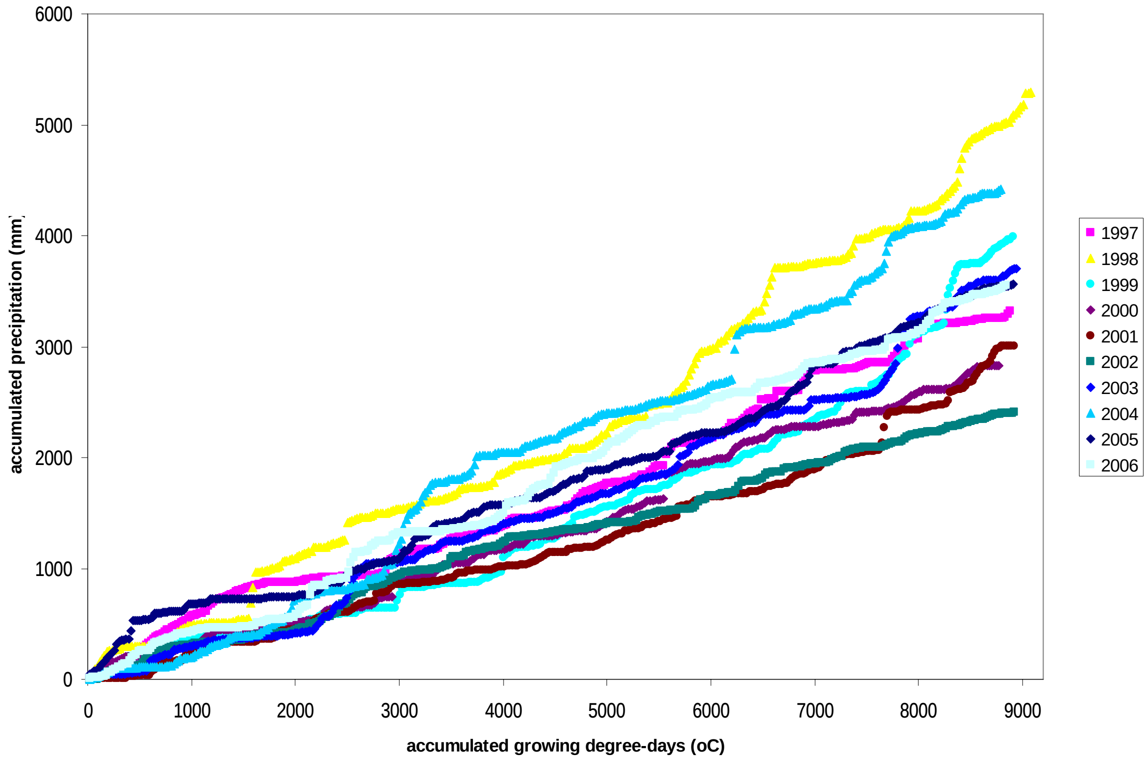
B.2. HJ ANDREWS



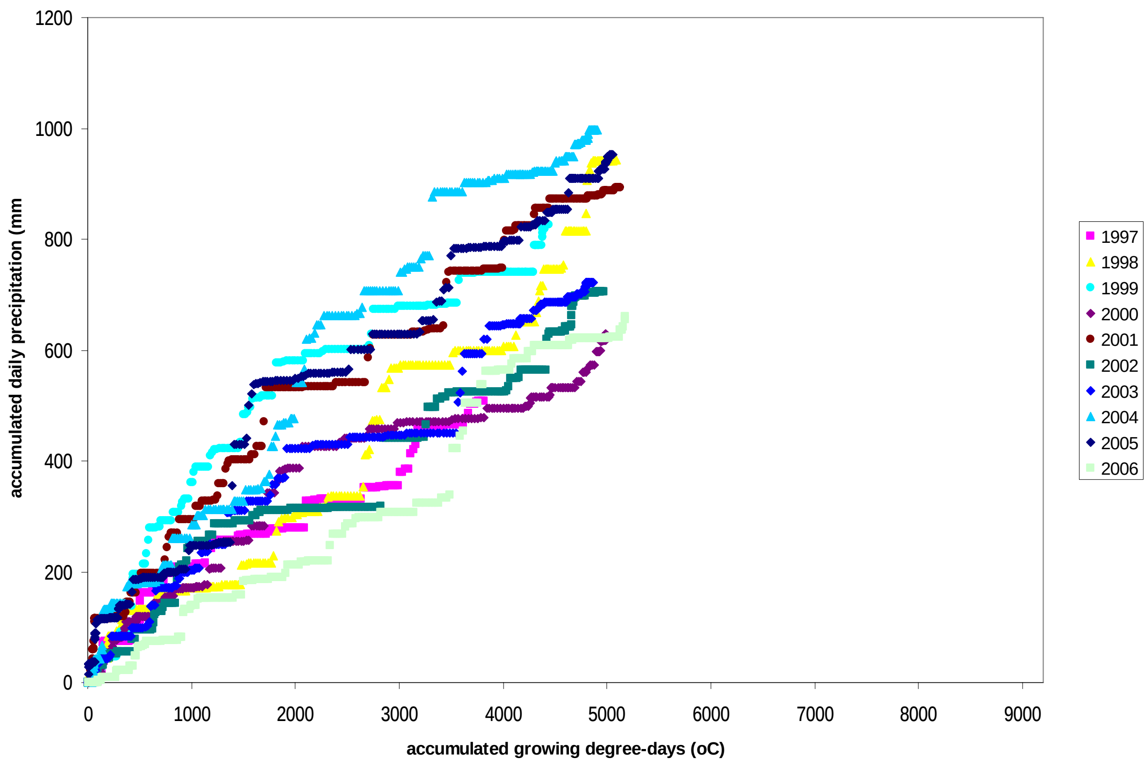
B.3. HARVARD FOREST



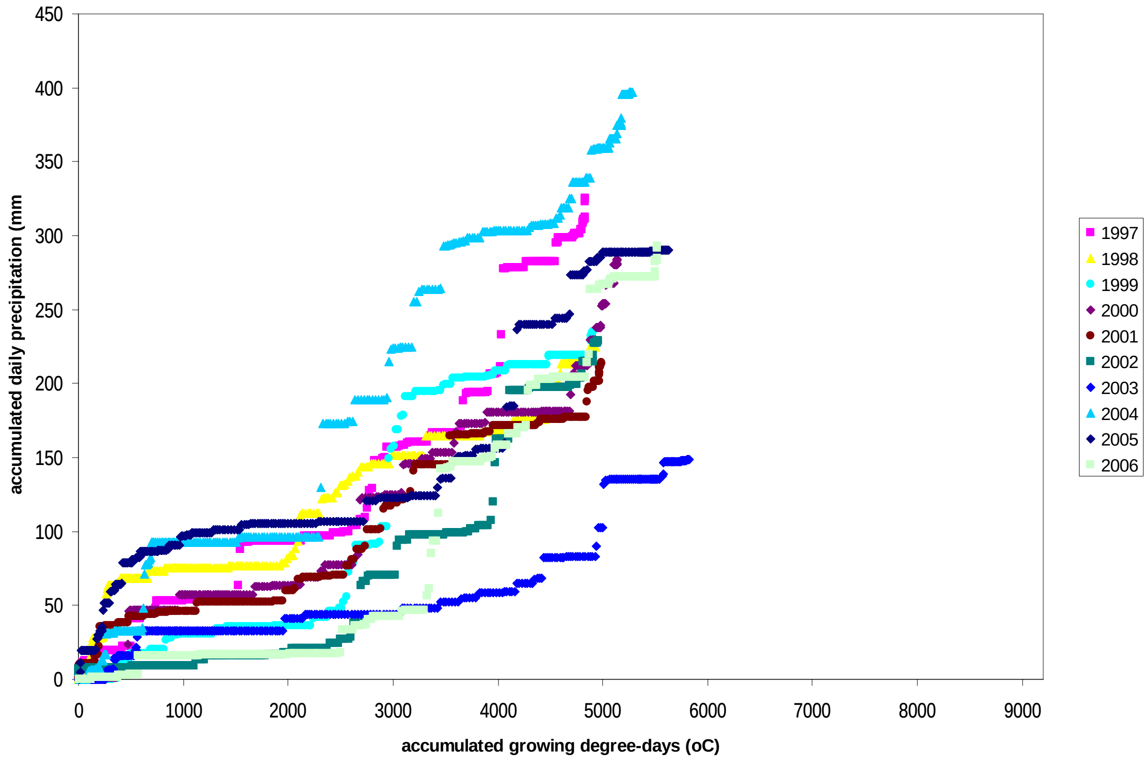
B.4. LUQUILLO



B.5. KONZA



B.6. SEVILLETA



B.7. JORNADA