**LTAR Pest Monitoring Protocol**

Annual measurements of pest abundance will allow the LTAR network to understand spatial and temporal variation in pest problems and examine the influence of management and climate on pests. Here we define pests as unwanted species (weeds, insects, plant pathogens, and vertebrate pests such as feral pigs or rodents) that adversely influence agricultural productivity or other ecosystem services.

**Temporal and Spatial Scale**

The temporal scale of interest is annual, to allow study of how climate influences Pests. The spatial scale of interest is field scale (i.e. fetch of the eddy-covariance towers) to allow data to be used in combination with most LTAR measurements. The number and array of subsamples necessary to accomplish this will depend on the degree of spatial variation. For sites that measure pests within both BAU and ASP treatments (Objective 2a, below), field-scale measurements would be conducted within each replicate of each treatment.

**Objectives**

1. Core measurements:
   1. Determine **biomass** of weeds. A primary focus on weeds is based on (1) the need to have comparable measurements across sites (2) the assumption that they will be present and at least somewhat problematic at all LTAR sites [Caveat: this is being drafted by a plant ecologist]. The focus on biomass should allow us to measure the proportion of productivity made up by weeds.
   2. For agroecosystems with serious insect, pathogen, or vertebrate pest problems, measure the **damage to plants** caused by key pests. To understand the severity of pest problems across LTAR sites, it is necessary to measure the most problematic pests at each site, regardless of pest type. Where insects, pathogens, and vertebrate herbivores are not among the most problematic pests, measurement of weeds is sufficient.
2. Optional measurements [might be emphasized more or less depending on feedback from sites regarding applicability and feasibility]:
   1. Determine **biomass and/or damage** in both BAU and ASP treatments. Substantial shifts in management often strongly influence pest problems, either directly, due to pest management, or indirectly, due to shifts in the suitability of the environment for pests. Therefore measuring pests in both BAU and ASP should help elucidate the mechanisms behind differences in agricultural performance.
   2. Determine the **impact** of weeds, insect pests and/or pathogens. Impact on agricultural productivity or other ecosystem services is the most relevant measure of pest problems, but can be challenging to measure. For sites where active control efforts are part of management plants, untreated controls can often be used to estimate impacts.

**Measuring biomass of weeds (objective 1a)**

*Defining weeds:* In cropland, weeds often include all non-crop species. In rangeland, weeds often include non-native species that are particularly abundant (often labelled “invasive plants”) and/or native species that cause problems by reducing forage quantity/quality or directly interfering with livestock (e.g., poisonous plants or undesirable woody species).

*Methods for measurement:* Biomass can be measured both directly, through harvesting, or indirectly through measurements of cover or abundance. Because weed impacts most often result from multiple species, we focus on total biomass of all weed species present rather than individual species. We recommend several options:

1. *Piggybacking on the ANPP measurements to measure weed biomass*. Where spatial variation is low, weeds can be separated from other plants in all or a subsample of ANPP harvest plots.
2. *Separately harvesting weed biomass*. Where spatial variation is high, ANPP samples may not capture weeds. In such cases, weeds can instead be harvested from subplots laid out to provide reasonable estimates of mean weed biomass. Subplot size and layout will depend on the site, but typically, this will mean using more small subplots. Separate estimates of weed biomass can still be used to estimate the proportion of productivity made up by weeds, by dividing mean estimates of weed biomass by mean estimates of total biomass (that is, if ANPP is being measured in the same area, it will not also be necessary to measure ANPP in the same plots used to measure weed biomass).
3. *Piggybacking on weed cover measurements from modified Whitaker plots (see Biodiversity Protocol), and relating cover to biomass.* Because visual cover estimates or counts of individuals can often be easier than measuring biomass, measuring cover or abundance may enable sites to better capture spatial variability and/or save time. Visual cover estimates also involve more subjectivity. Therefore it is important that efforts are made to standardize measurements across observers and years. For example, multiple sizes of cardboard squares can be used to represent different % cover values for 1 m2 plots. Images containing known % values for common species can also be helpful for standardization. To estimate biomass from these non-destructive measurements, we recommend that linear relationships be developed between weed biomass from weed cover. Assuming that such relationships are reasonably consistent over time within a site, cover measurements can then also be used to estimate the proportion of productivity made up by weeds. To develop linear relationships both cover measurements and destructive harvests can be conducted in a set of plots chosen to represent a range of weed abundance.
4. *Separate measuring weed cover and relating cover to biomass.* If modified Whitaker plots do not adequately capture weed populations, that cover sampling can be expanded or replaced with a design specifically aimed at capturing weed cover. As in #3, linear relationships would need to be developed to relate weed cover to biomass.

Measurements should be timed to match peak production of weed species, which will often but not always match that of non-weed species. At a minimum, measurements should be conducted within one primary, instrumented site. Preferably measurements would be conducted within both BAU and ASP sites.

**Measuring damage caused by insects and/or pathogens (objective 1b) [Note: this section needs to be evaluated and expanded by people with relevant expertise].**

For agricultural ecosystems in which insects or pathogens cause serious problems, we recommend measuring damage to plants. We focus on damage because it is likely to be easier to measure than abundance of pests themselves, and is closely related to impact. Examples of damage metrics would include % leaf area chewed/infected, % of yield damaged/lost. Damage should be measured just prior to harvest (or at peak production in rangeland/pasture), both to capture most of the damage that occurs within a season, and ensure that measured damage that is relevant to productivity/yield. Damage measurements can focus either on damage from particular pests, or on total damage from a community of pests, depending on which is more tractable and/or relevant for understanding pest impact.

**Measuring impacts of weeds, insects and/or pathogens.**

In agricultural ecosystems where pests are actively managed, untreated control plots can be used to estimate pest impact. The objective is to measure the difference in productivity, yield, or other ecosystem service (e.g. soil C), between plots with and without pests. Because management is rarely 100% effective, an estimate of the management efficacy (e.g., % reduction in pest population or damage) will be an important covariate. Where pests are managed within patches, it will be important to record either the area of management (if known) or estimates of pest biomass or damage, to scale impacts up to the field/landscape scale (e.g., by using the % of plots with high enough biomass/damage to warrant management).