Texas Parks and Wildlife Department

Missouri Resource Assessment Partnership

Ecological Mapping Systems of Texas: Summary Report

April 2014

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Citation:

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Abstract

A 398 class, 10 meter spatial resolution current vegetation map was completed for the state of Texas. The national Ecological Systems Classification provided the fundamental mapping targets. Land cover from 3-date, 30 meter resolution satellite imagery, and abiotic site types from digital county soil surveys and DEM-derived variables, were used together to model the current vegetation. This was accomplished by attributing land cover and abiotic variables to 10 meter resolution image objects generated from NAIP photographs, and then executing expert rules in the form of: land cover + abiotic variables = mapped type. Hence each image object was assigned a current vegetation type based on expert rules. In some regions, enhanced satellite land cover classification or landform modeling efforts were completed to map important current vegetation types. Additional ancillary data, including stream and road centerlines, were used to map some types. More than 12,000 spatially specific, quantitative ground data samples were collected in support of the mapping effort and to complete descriptions of mapped types. Significant overall improvements over existing maps included better spatial and thematic resolution, the mapping of many live oak types throughout the state, the mapping of evergreen versus deciduous shrublands in appropriate regions, the mapping of a wide variety of disturbance types, and the mapping of types over unique soils (e.g. salty, deep sand, gyp-influenced). These results will be used by a wide variety of partners in Texas for conservation planning and management, and methods are currently being used to develop a seamless map of Oklahoma. The abiotic site variables generated via this effort have been combined and simplified to define 97 distinct abiotic site types, and these will be used to help define management options and to facilitate revisions to the Ecological Systems map over time.

Background

The Texas Parks and Wildlife Department's (TPWD) mission is to help manage and conserve the resources of Texas. To accomplish this overarching goal, the location and extent of the current vegetation of the state must be mapped. The Texas Water Development Board (TWDB) also needs accurate vegetation maps to manage the water resources of the state. All players recognized that existing maps did not provide information that was accurate enough to serve critical needs and that conservation and management efforts were suffering as a result. Therefore, TPWD, with key help from TWDB, undertook an effort to create a better map that would serve current needs, and provide a platform for on-going up-dates and improvements.

Through a competitive process, the Missouri Resource Assessment Partnership (MoRAP) was selected as the primary contractor to help produce the statewide vegetation map. Initially The Nature Conservancy, and later NatureServe, was part of the team that helped identify mapping targets. The project was launched in late 2007, with what was envisioned as extending across a five-year time horizon. In 2008, TPWD was already working on a map for the Panhandle and far west Texas, and was seeking additional funds to complete that region, which were eventually provided by the US Fish and Wildlife Service, Great Plains Landscape Conservation Cooperative. MoRAP was charged with completing the rest of the state excluding the Trans-Pecos, because funding was initially lacking. The Trans-Pecos region was added during the course of the project. Thus the final time line extended across six full years, 2008 – 2013, and was completed in "Phases" that were defined based on the footprints of satellite images (Figure 1).

Product Specifications and Work Flow

Product Specifications

The original satellite-based landcover map produced by the Texas Parks and Wildlife Department (McMahan et al. 1984) represented a ground-breaking effort. That map was updated by more recent products, including the newest National Landcover Dataset (NLCD) (http://landcover.usgs.gov/uslandcover.php), the USGS GAP Analysis dataset (http://gapanalysis.nbii.gov/portal/server.pt), and the national LandFire map (http://www.landfire.gov). All of the recent maps resulted in 30 meter resolution datasets, appropriate for planning at regional and statewide scales of resolution. None of these maps seemed adequate to facilitate management and conservation efforts at fine enough spatial and thematic (number of mapped types) resolution.

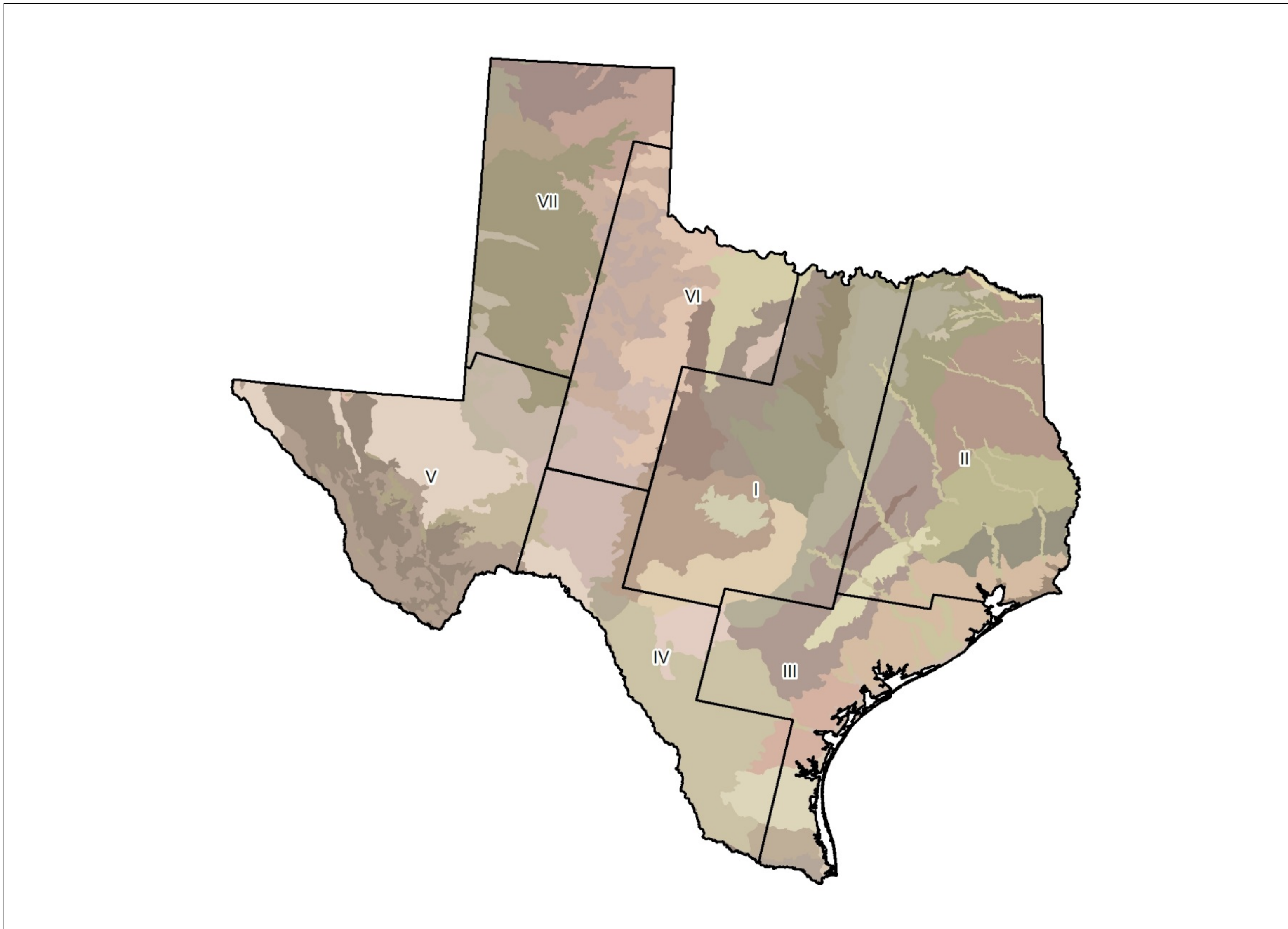

Figure 1. Texas Ecological Systems Mapping phase map, with outlines superimposed on EPA Level IV ecoregions. Outlines of the phases correspond with the footprints of satellite scene data. The project was completed in the spring of 2014.

TPWD facilitated meetings with internal staff and external partners with an eye toward creating a map product that would better satisfy needs. Product specifications emerged from this effort, and the production team developed strategies to meet standards:

Product Specification	Response of Production Team
Mapped types must conform to standardized classification	Ecological Systems Classification adopted
Ground-collected data must drive classification and mapping	>12,000 standardized, quantitative ground points helped drive the classification and mapping
Finer spatial resolution than national products	Image objects created at 10 m resolution, 9X finer resolution than national products
Finer thematic (more mapped types) than national products	Improvements in remote sensing (e.g. water regime, addition of live oak), successional status (e.g. disturbance types), and abiotic variables (e.g. steep slope, deep sand) were made; ultimately 398 types were mapped
Accuracy standards must be met	80% accuracy was achieved at the Ecological System level
Modifications and up-dates must be straightforward	Polygon-based results facilitate modifications; enduring feature data layer and keys to mapped types are in development
Ease of access and interpretation must be ensured	Interpretive materials have been developed and production of a web-based product is in development

Work Flow

Specific methodologies and work flows evolved during the course of the project, but the general process remained fairly constant in broad outline (Figure 2). Aspects of work flow included coordination between TPWD and MoRAP, and coordination among MoRAP staff members with diverse skill sets on the fairly intensive and complex set of tasks performed for each phase. In broad outline, these steps included:

1. Identification of mapping targets. This step took the shape of six, phase-specific, 1.5 day meetings with staff from TPWD, MoRAP, and NatureServe, and from a variety of partners with expertise specific to each phase. Draft mapping targets were developed from the Ecological Systems classification for the USA (MoRAP lead).

2. Collection of field data. A standardized, quantitative, spatially specific methodology was used to collect >12,000 field observations (TPWD lead).
3. Remote sensing classification of land use/landcover. Three date mosaics of Thematic Mapper Satellite Imagery were used to perform a supervised classification for each phase (see methods, below). The classification targets, usually about 15, were not identical for each phase, but rather were phase-specific in some cases (MoRAP lead).
4. Development of abiotic information. Soil groups from county digital soil surveys formed the backbone of this effort, and the development of these from information supplied by the National Resources Conservation Service (NRCS) was an iterative process. Soil groups were created, viewed, and revised, sometimes by hand, as needed. Digital elevation model (DEM)-derived variables were also used. These included % slope, land position, and solar insolation (the amount of sun striking a spot, which varies with slope exposure and percent). Stream buffers and ecoregions were also considered abiotic variables for modeling (see step #7)(MoRAP lead).
5. Development of image objects (segmentation) from air photos at 10 m resolution. In some phases, input data for object creation was from a single variable generated from 3- or 4-band air photos (see methods, below)(MoRAP lead).
6. Attribution of image objects with land use/landcover (step #3) and abiotic variables (step #4). The attribution of small image objects with information from several separate data sources, each with their own spatial resolution and source, was an involved process that required tiling and systematic application of rules for dealing with issues (MoRAP lead).
7. Development and application of a current vegetation classification and mapping models based on the attributes assigned to image objects in step #6. This was an iterative process that required on-screen viewing and revision of results. The end result of this step was a draft ecological systems map for a given phase (MoRAP lead).
8. Development of final map and database. This step often involved use of ancillary data, such as roads, to improve the look of the map, and, after Phase 1, to match with results from earlier phases. Edge matching among phases was facilitated by the vector-based (polygon) nature of results (see methods). A number of corrections have already been made to earlier phases of the final map (TPWD lead).
9. Development of interpretive materials and final geodatabase. This involved modification and additions to technical descriptions of ecological systems and mapping subsystems that corresponded with mapped types, plus development of new, short descriptions of mapped types. This step also resulted in phase-specific summaries and caveats for users. MoRAP was initial lead on this task,

but further development of web-based materials and expansion of content is underway at TPWD, which will be the stewards of the data.

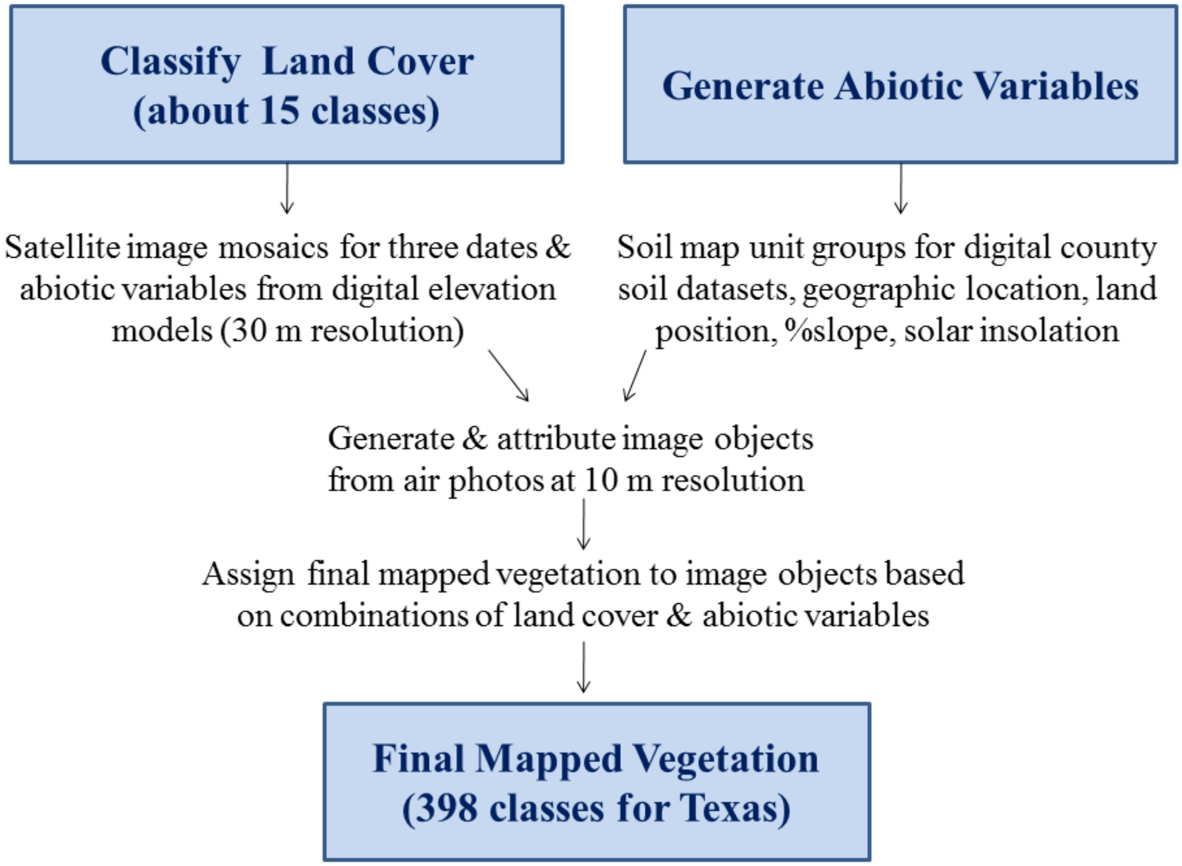

Figure 2. General outline of methods used to classify and map current vegetation.

Methods

Development of Classification, Mapping Targets, and Naming Conventions

Numerous classifications have been applied to the vegetation of Texas. Prominent among these is the classification used by McMahan, Frye, and Brown (1984) for their Texas Parks and Wildlife Department mapping effort. While extremely useful, the vegetation types they identified were not broadly accepted beyond Texas and were succeeded by other classifications. In 1987, Diamond, Riskind, and Orzell developed the series level of classification while working at the Texas Parks & Wildlife Department. This classification conformed to existing national and international standards in place at the time, following a physiognomic/life form protocol developed in Europe (Mueller-Dombois and Ellenberg, 1974). Diamond and others continued to refine this classification, and it has been widely used in conservation planning, but has not been applied to mapping projects, except at relatively local scales. The classification developed by Diamond, Riskind, and Orzell (1987), and developed for other regions across the nation by different ecologists, has been continuously worked on by ecologists within The Nature Conservancy (TNC) and NatureServe, after that organization was spun off from TNC. This effort resulted in the current U. S. National Vegetation Classification System (NVCS). The finest levels of the NVCS, the Association and Alliance, have been used for mapping (e. g. a modified Alliance classification was used for GAP Analysis products for Texas). Associations are generally considered too fine for large-area mapping.

In developing the legend of vegetation types that we mapped, we chose to use the Terrestrial Ecological Systems classification developed and maintained by NatureServe (NatureServe, 2003). Ecological systems are defined as groupings of plant communities that tend to co-occur on the landscape and share similar ecological processes, substrates, and/or environmental gradients. This classification characterizes units at a scale amenable to the application of remote sensing and abiotic modeling that we used to map vegetation types. In addition, the classification provides a framework that is recognized nationally and internationally, has been developed by dozens of ecologists over more than ten years, and will therefore result in products that will be recognized and useful beyond the bounds of the state of Texas. Other projects, such as Landfire (http://www.landfire.gov), Southwest Regional Gap Analysis Project (http://fws-nmcfwru.nmsu.edu/swregap/), and Southeast Gap Analysis Project (http://www.basic.ncsu.edu/segap/), have also used terrestrial ecological systems for mapping vegetation.

We mapped multiple vegetation types that are components of the more broadly defined ecological systems. We called these mapping subsystems “Mapped Vegetation Types”, and they typically represent the various landcovers (e.g. broadleaf evergreen forest, deciduous forest, evergreen shrubland, grassland) that constitute the full range of variation within an ecological system, depending on land use history or successional state. Ruderal or disturbance vegetation types also dominate large areas of the landscape, and these were generally mapped as native invasive or non-native invasive types.

Terrestrial ecological systems do not fit hierarchically within the NVCS. However, they do represent groupings of vegetation communities that are represented by Associations within the NVCS. Therefore, while these finer units of vegetation classification do not nest uniquely within a given ecological system, they can be associated with one or more ecological systems and can be useful in the identification and characterization of systems. Alternatively, mapped ecological systems will be useful in identifying areas that may harbor a given suite of Associations.

Naming Conventions. We developed a naming convention for mapped vegetation types that incorporates regional relationships of the types, as well as descriptive information about the composition or structure of the vegetation. Generally, types that show some (though not necessarily perfect) fidelity to a particular region have names that begin with the region's name followed by a colon. This reference is then followed by a descriptive phase that includes reference to the dominant species where possible (e.g. Post Oak), and to the structural character of the type (e.g. Woodland). If more than one dominant species or group of species is identified, then these are separated by a hyphen "-". This suffix portion of the name may also include a descriptor of the landform that the type occupies (e.g. Slope), or a unique edaphic feature characterizing the type (e.g. Sandyland). These names retain explicit relationships to the Ecological Systems Classification and can be easily referenced relative to those concepts. Types resulting from human-related activities and not attributable to particular ecological systems lack the geographic region as a prefix, but may be prefixed by terms that indicate they are non-natural (e.g. Disturbance, Native Invasive, Non-native Invasive). Decisions related to designations as non-natural were based on expert opinion as informed by existing literature, field experience, and prevailing natural vegetation assigned to ecological site types (aggregations of soil map unit types) by the Natural Resources Conservation Service (NRCS). For example, evergreen shrubland on former prairie soils is often labeled "Native Invasive: Juniper Shrubland." We mapped and labeled some human-associated types such as urban and row crops directly from the decision tree landcover classification.

Collection of Field Data

TPWD and partner personnel collected ground data on landcover, composition, ecological system, and mapped vegetation type using a legend developed via expert committee. The starting point for the legend was NatureServe's Ecological Systems classification, but this was supplemented with an eye toward mapping all landcover types within each Ecological System if those cover types existed. In addition, agricultural and other human-related types were included in the legend. An estimated total of 460 days were spent field sampling at an estimated 12,192 locations. Phase-by-phase notes are provided in Appendix 1.

The general data collection procedure included:

1. Sample plots were located either near a road or on accessible private or public lands. Locations were precise, based on use of a GPS (usually Trimble 232 with +/- 3 meter accuracy) linked to ESRI (ArcMap 9.0, 9.3 and ArcMap 10.0) GIS software on a computer in the field vehicle. Samples sites were selected based

on road or property access and variation in image signature or mapped soil types (i.e.; high diversity in landcover and mapped soils types was desirable)

2. Samples along roads were collected at approximately one-mile intervals, often on both sides of the same road, starting from a random location. In addition, samples were collected at many stream/road crossings, and where uncommon plant communities were noted. On-the-ground samples were collected on some public and private lands. When possible, field data were collected across the full diversity of abiotic site types (e.g. soil types, slopes) on any given property.
3. For data collected along roads, we were limited to views from the right-of-way, air photography, and other environmental data layers loaded on the laptop, including county SSURGO soils and the Geologic Atlas of Texas from the Bureau of Economic Geology. Where trees obscured the view away from the road, we relied primarily on photos and road-side observation to select a sample plot of relatively homogeneous vegetation. All sample plots were located at least 30 meters from the road within the center of a square with sides of at least 50 meters, to help ensure that the footprint a corresponding 30 meter satellite pixel fell within a homogeneous land cover patch.

We collected a standardized suite of data using a computerized feature data form with drop-down windows to reduce mistakes, and we took a picture at most site locations (Table 1, Figure 3). In later phases, fields were added to capture succulent cover and dominant succulent species. Drop-down lists used plant names from the USDA Plants database. Initial species lists for Phase 1 were developed from the literature, and new species were added as we proceeded through each new phase of the project.

Table 1. Example of information within the feature database used for field data collection.

Field Name	Data Type	Example Value(s)	Description
SampleDate	Date	9/21/2007	Date sample taken.
TeamLeader	Text	Duane German	Name of data collection team leader.
SiteID	Integer	291	Unique identifier for sample site.
PictureID	Integer	421	Unique identifier for each sample site photo.
EcoSysName	Text	Edwards Plateau Floodplain Terrace	Name of Ecological System from the map legend (see Appendix 1).
EcoSysConf	Text	High	A categorical value expressing team leader's confidence in correctness of Ecological System identification. Values: High, Good, Medium, Low.

Table 1. Example of information within the feature database used for field data collection (continued).

Field Name	Data Type	Example Value(s)	Description
LandCover	Text	Grassland	Name of the landcover class (see Table 2)
Woody_PC	Text	0-5	Total percent cover of all woody vegetation - categorical data 0-5, 6-25, 26-50, 51-75, 76-100
BLEG_PC	Text	26-50	Total percent cover of all broad-leafed evergreen trees - categorical data 0-5, 6-25, 26-50, 51-75, 76-100 -- must be less than or equal to Woody_PC
NLEG_PC	Text	76-100	Total percent cover of all needle-leafed evergreen trees - categorical data 0-5, 6-25, 26-50, 51-75, 76-100 -- must be less than or equal to Woody_PC
Tree_PC	Text	26-50	Total percent cover of all trees - categorical data 0-5, 6-25, 26-50, 51-75, 76-100 -- must be less than or equal to Woody_PC
Shrub_PC	Text	25-Jun	Total percent cover of all shrubs - categorical data 0-5, 6-25, 26-50, 51-75, 76-100 -- must be less than or equal to Woody_PC
Herb_PC	Text	0-5	Total percent cover of all herbaceous plants - categorical data 0-5, 6-25, 26-50, 51-75, 76-100
Tree1	Text	*Ulmus crassifolia*	Scientific name of **most** visually dominant over-story tree species in plot area. This is a single-trunked perennial woody plant of greater than 5 meters in height. NA if none present.
Tree2	Text	*Carya illinoinensis*	Scientific name of **second most** visually dominant over-story tree species in plot area. This is a single-trunked perennial woody plant of greater than 5 meters in height. NA if none present.
Tree3	Text	*Quercus fusiformis*	Scientific name of **third most** visually dominant over-story tree species in plot area. This is a single-trunked perennial woody plant of greater than 5 meters in height. NA if none present.

Table 1. Example of information within the feature database used for field data collection (continued).

Field Name	Data Type	Example Value(s)	Description
Shrub1	Text	*Juniperus ashei*	Scientific name of **most** visually dominant shrub in plot area. Shrub is defined as woody perennial plant, usually multi-trunk, between .5 meters and 5 meters in height. Will contain NA value if no shrubs present in plot.
Shrub2	Text	*Prosopis glandulosa*	Scientific name of **second most** visually dominant shrub in plot area. Shrub is defined as woody perennial plant, usually multi-trunk, between .5 meters and 5 meters in height. Will contain NA value if no shrubs present in plot.
Shrub3	Text	*Sapindus saponaria*	Scientific name of **third most** visually dominant shrub in plot area. Shrub is defined as woody perennial plant, usually multi-trunk, between .5 meters and 5 meters in height. Will contain NA value if no shrubs present in plot.
Herb1	Text	*Cynodon dactylon*	Scientific name of **most** visually dominant herbaceous plant in plot area (1/4 acre). Include woody vines. Will contain bare ground if no herbaceous plants are present.
Herb2	Text	*Bothriochloa laguroides*	Scientific name of **second most** visually dominant herbaceous plant in plot area (1/4 acre). Include woody vines. Will contain NA if bare or only one species present.
Herb3	Text	*Panicum virgatum*	Scientific name of **third most** visually dominant herbaceous plant in plot area (1/4 acre). Include woody vines. Will contain NA if bare or only one species present.

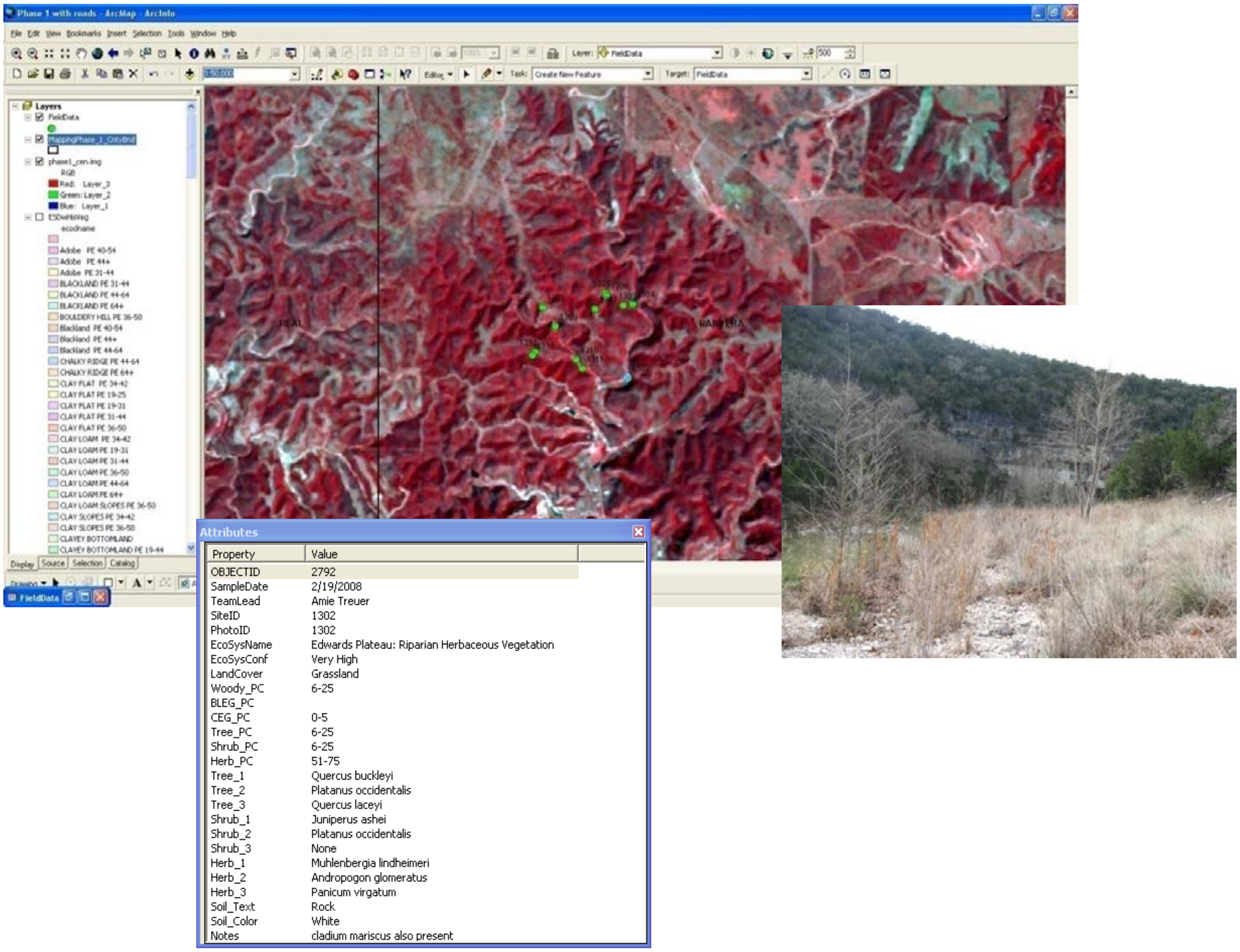

Figure 3. Screen-capture of ground verification data collection database schema (lower left), overlay of data plots on satellite image, and example of a photograph taken at one data plot.

Remote Sensing Classification

We used three dates of Landsat Thematic Mapper satellite data, combined with other information, to classify the landcover. For Phase 1, for example, this involved acquisition of five LandSat path-row scenes (Table 2). After data acquisition, the next step in the classification process was to create a seamless mosaic of LandSat scenes for all dates (Figure 4).

The generation of the mosaics was neither a straightforward nor a simple task. The imagery used to build the mosaics needed to be, for the most part, cloud-free. This condition rarely exists in practice. Because of clouds, often a given path-row of imagery was itself a mosaic. Maintaining a consistent date throughout each seasonal mosaic brought additional complexity to the process. The most challenging step in generating the seasonal mosaics was the issue of color balancing. This process removes the apparent divisions among adjacent path-rows of imagery by matching, on a band by band basis, the histograms of all the images used. This process is iterative in nature and is often one of the most labor intensive portions of the landcover mapping protocol.

We used a decision tree classification approach to classify the initial 15 landcover classes for Phase 1 (Table 3). This approach allows for the combination of remotely sensed data with ancillary data in a flexible way. We tried multiple different combinations of satellite reflectance data and ancillary data before settling on a final combination that provided the best result. Important ancillary data used for classification (in addition to all 6 LandSat reflectance bands for three dates), included; slope, aspect, landscape position, solar insolation, percent canopy cover from the National Landcover Dataset (NLCD), percent impervious surface from the NLCD, and agricultural areas as defined by the most recent version of the National Agricultural Statistics Service cropland data layer.

Table 2. Dates of satellite imagery used for Phase 1. Three season imagery mosaics were created for each phase.

Path/Row	Summer/Fall Leaf-on Date	Leaf Off Date	Spring Leaf-on
27/37	September 13, 2006	February 4, 2007	April 3, 2005
27/38	September 13, 2006	February 4, 2007	April 3, 2005
27/39	September 26, 2005	February 14, 2005	April 4, 2007
28/38	September 20, 2006	February 8, 2006	March 31, 2007
28/39	September 20, 2006	February 8, 2006	March 31, 2007

Table 3. Typical landcover classes derived directly from decision tree classification using three date imagery mosaics, digital elevation model-derived environmental data, and sometimes other data specific to phase. Examples are for Phase 1.

Landcover Class	Description	Examples from Phase 1 Area
Open Water	open water with little or no emergent vegetation	
High Intensity Urban	urban development, generally >70% impervious cover	city centers, highways
Low Intensity Urban	urban development, generally <70% impervious cover	residential areas
Barren / Sparsely Vegetated	little or no vegetation year-round	river beds, quarries, areas cleared for development, rural roads
Cold Deciduous Forest and Woodland	>25% total tree canopy (>4 m tall), where >75% of the relative cover is cold deciduous trees	Texas oak, cedar elm, sugar hackberry, post oak
Broadleaf Evergreen Forest and Woodland	>25% total tree canopy (>4 m tall), where >75% of the relative cover is broadleaf evergreen trees	plateau live oak
Coniferous Evergreen Forest and Woodland	>25% total tree canopy (>4 m tall), where >75% of the relative cover is coniferous evergreen	loblolly pine, Ashe juniper, eastern redcedar
Mixed Cold Deciduous / Evergreen Forest and Woodland	>25% total tree canopy (>4 m tall), where >75% of the relative cover is neither only cold deciduous trees or only evergreen trees	Texas oak, cedar elm, post oak with Ashe juniper, eastern redcedar, plateau live oak
Cold Deciduous Shrubland	>25% total canopy of trees and shrubs (<4 m tall), where the majority of the canopy is shrubs, and the majority of the woody plants are cold deciduous	mesquite, white shin oak, whitebrush
Evergreen Shrubland	>25% total canopy of trees and shrubs (<4 m tall), where the majority of the canopy is shrubs, and the majority of the woody species are evergreen	Ashe juniper, eastern redcedar, plateau live oak

Table 3. Typical landcover classes derived directly from decision tree classification using three date imagery mosaics, digital elevation model derived environmental data, and sometimes other data specific to phase. Examples are for Phase 1 (continued).

Landcover Class	Description	Examples from Phase 1 Area
Grassland	dominated by herbaceous vegetation, usually graminoid, with less than 25% woody cover. Includes both planted pasture and native prairie.	little bluestem, Texas wintergrass, King Ranch bluestem, Bermudagrass
Irrigated Sod Grass Farm	dominated by irrigated grass sod farming. May also include urban grassland areas such as parks and golf courses.	Bermudagrass, Johnsongrass
Row Crops	Row crop agricultural lands	sorghum, corn
Herbaceous Marsh	seasonally or semi-permanently flooded, or saturated soil wetlands dominated by herbaceous vegetation	rushes, sedges, grasses
Swamp	semi-permanently flooded woody wetlands dominated by woody vegetation > 4 meters tall	baldcypress

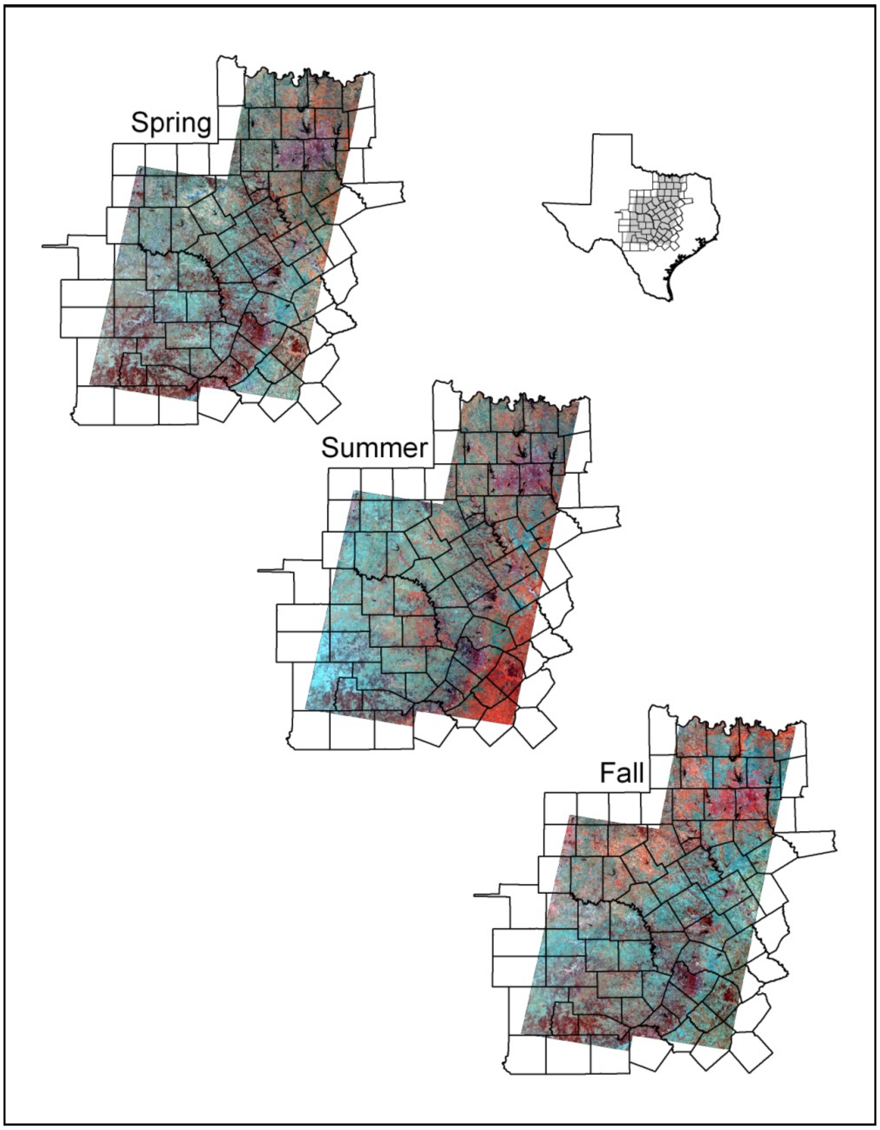

Figure 4. Spring, summer, and fall mosaics for five Landsat images were used for each phase (Phase 1 depicted).

The decision tree classification approach requires a training data set for each landcover class mapped. For Phase 1, for example, we generated this dataset via air photo interpretation (5,951 points) and ground-collected data (2,209 points). Air photo interpretation required the use of both leaf-on and leaf-off photos. Leaf-on photos were interpreted from National Agriculture Imagery Program (NAIP) photography collected in 2004 and 2005, whereas leaf-off photos were orthorectified color infrared images collected in 1996. Most photo-interpreted training points were generated via (1) generating a random grid of sample sites across the Phase 1 area, (2) zooming to those locations at 1:6,000 resolution, and (3) circumscribing visually homogeneous vegetation and assigning those points a landcover type using 2004, 2005, and 2006 leaf-on NAIP photographs and 1995-1996 StratMap leaf-off photography. Training data were also collected from a second set of points using digital vegetation maps from Texas Parks and Wildlife lands, including Mason Mountain Wildlife Management Area and Lost Maples State Natural Area. A final set of >12,000 training points came from on-the-ground data collection. We checked all ground-collected data using air photos and eliminated data points that appeared to fall within mixed landcover based on expert judgment. In all cases, point data were double-checked by a second worker using both leaf-on and leaf-off photography to ensure that the correct landcover type had been assigned to each point..

The decision tree classification process assigns pixels to landcover classes using the statistical relationship between the training data and the satellite imagery and ancillary data of a given area. All decision tree classifications were run using a 30m spatial resolution, which is the native spatial resolution for the Landsat Thematic Mapper imagery. The classification procedure was implemented multiple times, using different combinations of data, in an effort to maximize classification accuracy. Additional points were often required when areas of a known landcover type were consistently missed by the decision tree process. In those cases, staff inspected the high resolution aerial photography and identified additional sample points of the necessary landcover type. This process took advantage of staff ecological expertise and their experience identifying the landcover types of Texas. We generated more than 20 different classification results. The most accurate classification used satellite reflectance data from all three dates together with slope, aspect (divided into 9 equal classes), landscape position, solar insolation, percent canopy cover from the NLCD, percent impervious cover from the NLCD, and National Agricultural Statistics Service cropland designation (cropland or not cropland).

Ecological System (Current Vegetation) Classification and Mapping: Image Object Generation, Attribution, and Modeling

Image Object Generation and Attribution with Landcover. A one hectare minimum mapping unit (MMU) was specified for this project. To ensure that the MMU was achieved, a post hoc process was implemented using image objects generated with the eCognition Developer software (Figure 5). For most phases, image objects were generated from the first principle component of a NAIP image county mosaic that had been re-sampled to a 10m spatial resolution. This procedure was run for each county mosaic. Some counties needed to be divided into multiple pieces because they were too large to be processed individually. In Phase 1, for example, this resulted in 92 separate sets of image objects being developed. This process produced a shapefile containing polygons that represented homogeneous units (relative to the 10 m PCA result for each county mosaic). The image objects were then used to summarize the classification resulting from the decision tree classification procedure. The statistic of interest during the summarization process was the mode. ArcGIS was used to determine the mode for each object (nearly 10 million for Phase 1). The separate sets of image objects were then imported to a file geodatabase (Figure 3).

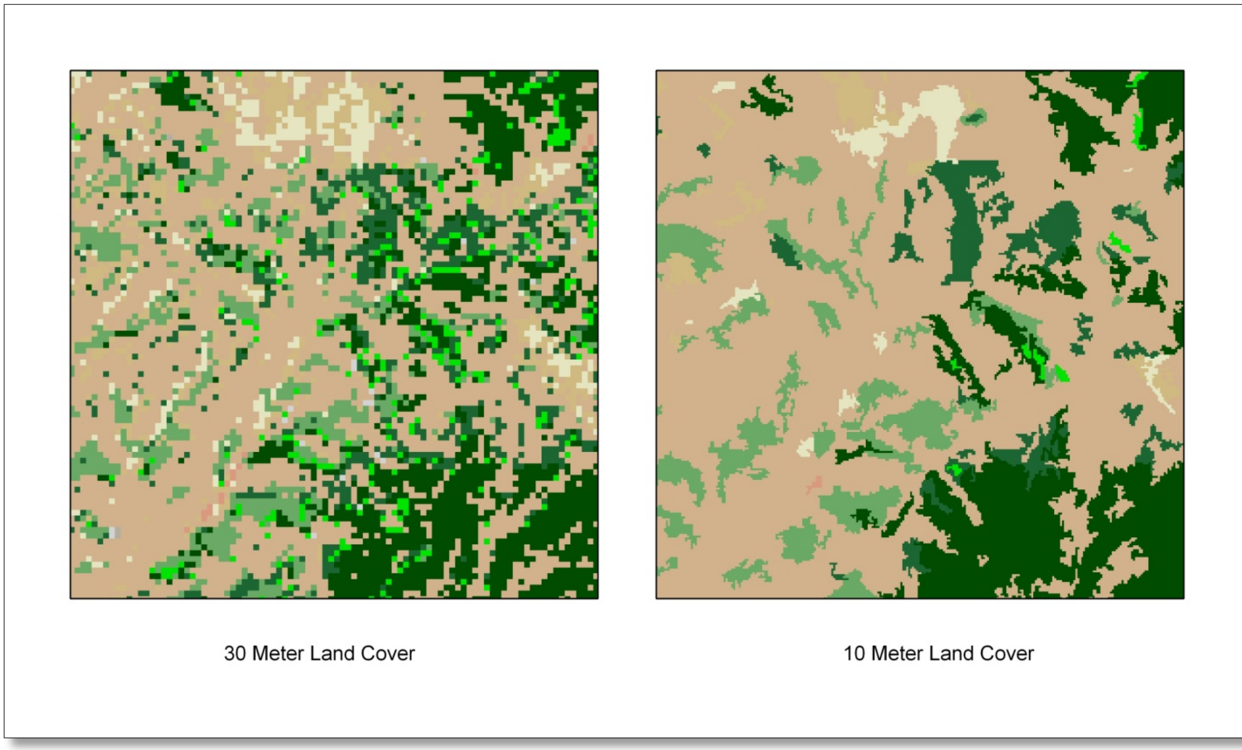

Figure 5. Illustration of the increase in spatial resolution from 30 meter pixels to 10 meter pixels. Image objects were generated from the first principle component of a NAIP image county mosaic that had been re-sampled to 10 meters.

Image Object Attribution with Abiotic Variables. Abiotic environmental data were generated and attributed to image objects, in addition to land cover data (Figure 6, Table 4). Methods evolved and different abiotic information was developed for different phases of the project. In summary, we attributed the following information to objects:

1. Soil group based on digital county soil map units provided by the Natural Resource Conservation Service (NRCS) Soil Geographic Database (SSURGO). We formed soil map unit groups by reference to ecological site type (ecoclassid in the SSURGO data tables; see http://soils.usda.gov/survey/geography/ssurgo/), by soil texture, and by flooding frequency. This process evolved over time, and we made less reference to ecological site type to form soil groups in later phases. Mixed soil map units (map unit polygons with more than one soil

component type) generally made up less than 10% of all soil polygons, and were assigned to groups based on the majority component for a given map unit.. Often, individual soil map units were assigned to groups based on selections done by hand, on-screen, or via geographic rules or other ancillary data. In later phases, we assigned a unique id to each soil map unit polygon to track all of the changes that we made to the soil map units based on ancillary data.

2. A riparian designation for pixels that fell on stream center lines taken from the 1:24,000 National Hydrologic Dataset (see http://nhd.usgs.gov/data.html). These riparian corridors were 30 m wide.
3. A %slope designation generated from 10 meter digital elevation models (DEMs; see USGS National Elevation Dataset, http://ned.usgs.gov/). In most phases, land cover on slopes greater than 20% were usually assigned to slope Ecological Mapping Subsystems, different from flatter areas, and slopes greater than 100% were designated as cliffs/bluffs.
4. Additional data derived from 10 m DEMs or geology layers were used in particular phases to target specific vegetation types. Variables used included elevation (used in the Trans-Pecos region, and in some areas of the Gulf Coast), landscape position (primarily used in the Pineywoods and Post Oak Savanna), solar insolation (used in the Trans Pecos), and ravines (used in the Pineywoods).

In addition, transportation corridors were 'burned in' to the final map by reference to center lines from US Census TIGER data (see http://www.census.gov/geo/maps-data/data/tiger.html) and Texas Railroad Commission railway data (see http://www.rrc.state.tx.us/forms/maps/).

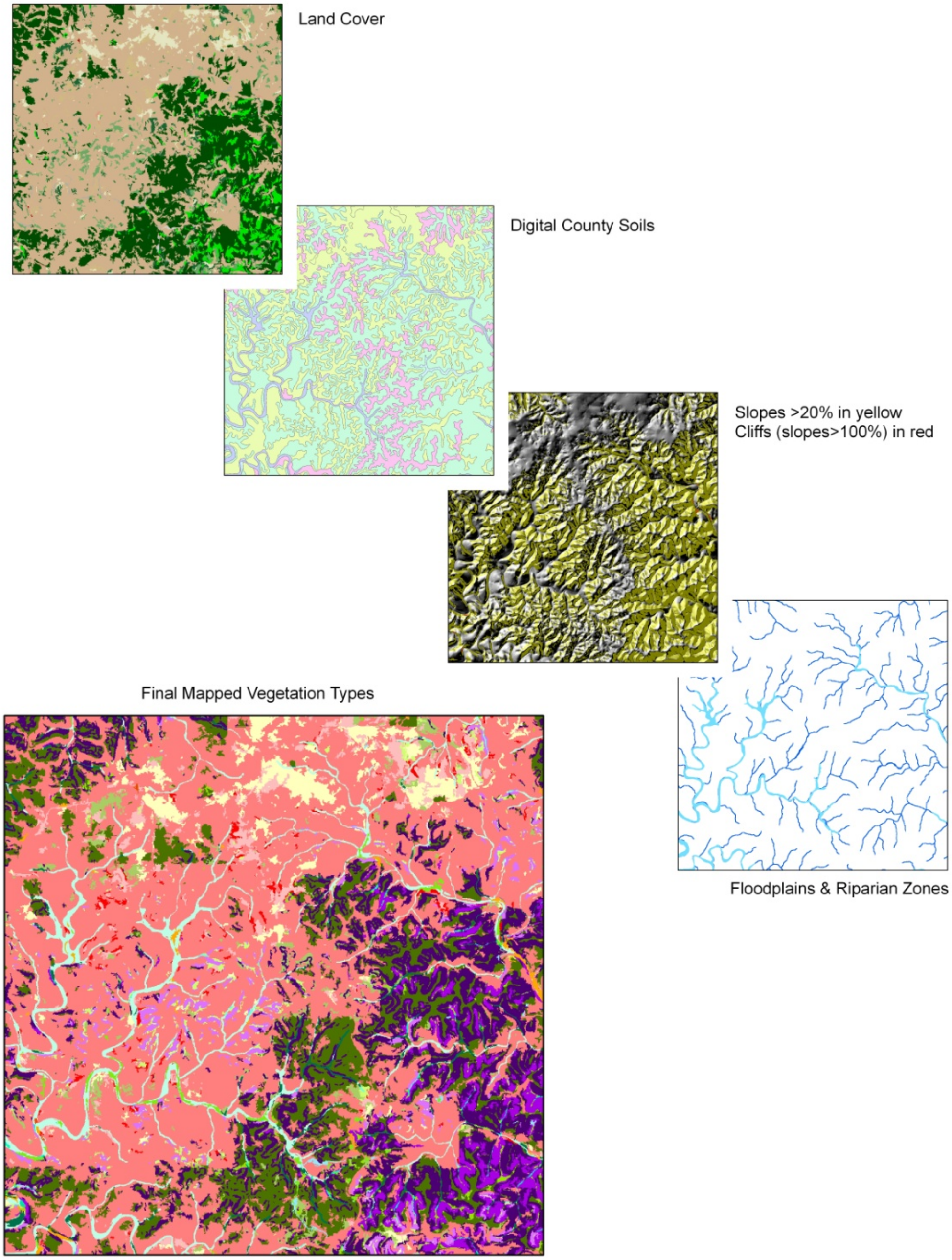

Figure 6. Example of data layers developed and used to map ecological systems, subsystems, and invasive types.

Table 4. Typical data sources used to map ecological systems, subsystems, and invasive types.

Data Layer	Comments
SSURGO Soils Groups	From NRCS digital county soil surveys. Initially assigned from ecological site type or texture, and often modified using ancillary data.
Floodplains	A special soil group from NRCS digital county soils surveys. Often modified on-screen or by using ancillary data.
Slope >20%	Generated from 10 meter digital elevation models. Used to identify all 'slope' mapped vegetation types.
Slope >100%	Generated from 10 meter digital elevation models. Used to identify all cliffs and bluffs
Riparian Zones	Defined as a 30 meter buffer on the streams identified in the National Hydrology Dataset at 1:24,000 scale. Used to identify all riparian mapped vegetation types.
Ecoregions	Based on EPA Level 4 ecoregions. Often used to correct mis-mapped SSURGO soils or help define the range of mapped types.
Elevation	Assigned from 10 meter digital elevation models. Used to map types in the Trans-Pecos and on the Gulf Coast.

Vegetation Modeling and Mapping.

Different combinations of landcover with different soils, slope, hydrology, or ecoregions were assigned to different final mapped vegetation types. For example, the cold deciduous forest landcover type on a floodplain was assigned and mapped as a floodplain ecological subsystem, whereas cold deciduous forest on a slope >20% was assigned and mapped as a slope forest, and so on (Figure 7).

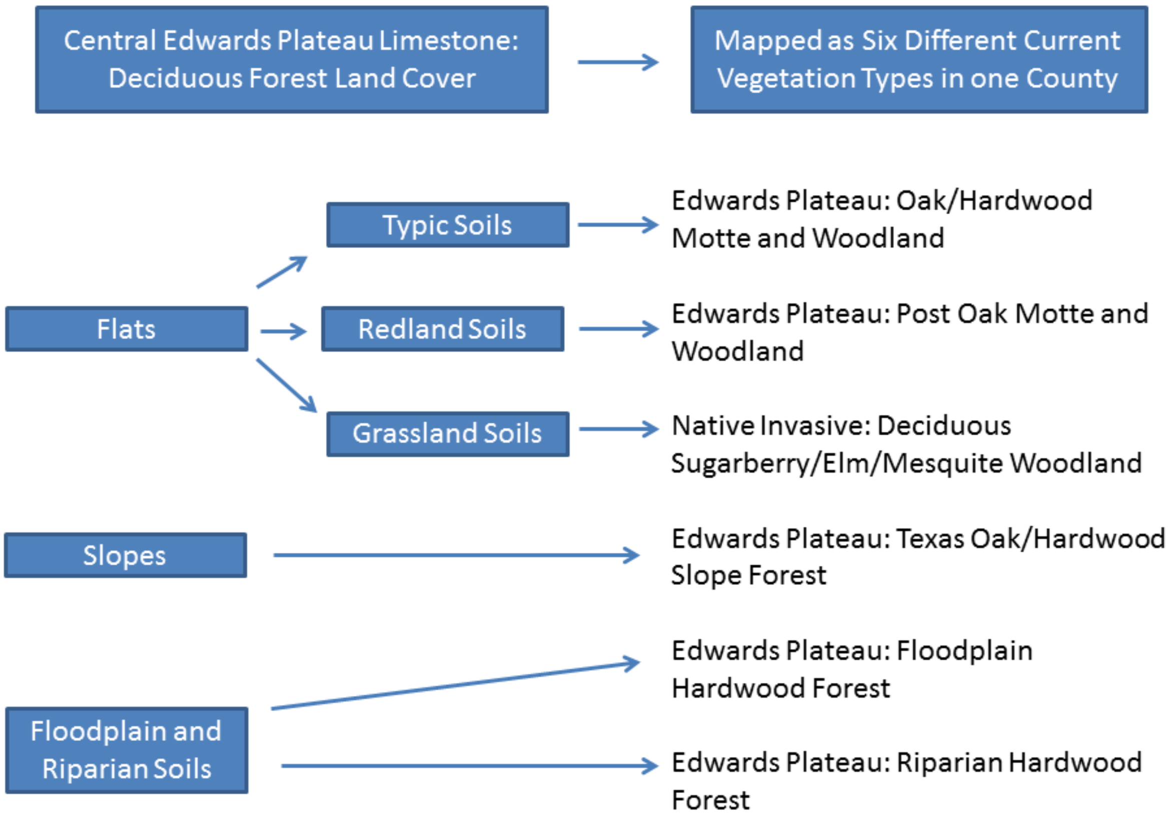

Figure 7. One landcover type (deciduous forest) may have been mapped as several different ecological system or subsystem vegetation types based on modeling.

Evolution of Technical Approach

Technical methods used to facilitate the modeling process evolved over time, but by Phase 4 of the project the methodology had stabilized. In Phases 1 and 7 (done independently by TPWD), the models were developed within an MS Excel spreadsheet where a row represented a given soil type and the columns represented each land cover type. For each soil/land cover combination, a specific mapped type could then be entered into the appropriate cell. For other phases, MS Access was used and this allowed the development of linked lookup tables, thereby constraining the possible selections for a soil/land cover combination and reducing the possibility of transcription error. This also allowed the incorporation of slope and riparian attributes into a single database and simplified the ability to export the dbf files to be joined to spatial data for model implementation.

Initially (Phases 2 and 3), models developed in MS Access were applied to attributed polygons (objects) using ArcGIS ModelBuilder. This graphical interface allowed modeling tasks to be codified such that any corrections made to the attributes or models could be re-applied without concern for user error during model application. However, the processes implemented in ModelBuilder were exceedingly complex, contained numerous steps, and produced complicated visualizations. This made it difficult to troubleshoot the implementation. So for the later phases (Phases 4, 5, 6, and the re-processing of Phase 1), python scripts accessing the ArcPy interface to ArcGIS were used and provided a more flexible and transparent method for model implementation. Additionally, much of the basic implementation of the models was accomplished inside MS Access using Visual Basic for Applications (VBA) applications. Accomplishing this part of the task was much more time efficient in MS Access than it was using complex joins and calculations within ArcGIS.

Results and Discussion

Even though 398 current landcover types were mapped in Texas, only a few made up the bulk of the area of the state. The most common mapped type was Row Crops at 10.8% of the total area (Table 5). It was greater than 75% more common than the second most abundant type, which was Native Invasive: Mesquite Shrubland (6.1%). Only 25 types accounted for more than 1% of the area of Texas each. Together, these types accounted for 61.9% of the total area of the state, whereas the remaining 373 types accounted for the remaining 38% of the total area. A total of 343 types accounted for less than 0.5% of the area each, and 273 types made up less than 0.1% of the area each. Some of these types are simply rare but unique and of conservation significance, whereas others may not be significant. Efforts to merge rare and closely related communities would improve the utility of the map for many users, and some modifications have already been tried by Texas Parks & Wildlife Department and possibly other users.

The common description of mapped types is based in part on quantitative field data points. The 25 most common mapped types contain 52.7% of the field data points and account for 61.9% of the area (see Appendix 1). A total of 111 types contained >20 sample points, 68 types contained >50 points, 34 types contained >100 points, and 16 types contained >200 sample points. Five or fewer sample points were contained within 213 types, and 99 types were not sampled. Thus, professional judgment was largely relied upon to describe more than 200 of the 398 mapped types. Additional field data would help define these types, especially for those that are of conservation concern.

Table 5. Twenty-five mapped types made up >1% of the land area of Texas each, and together account for 61.9% of the total land area of the state. Relative condition (1 to 5) indicates how closely the current mapped type retains the historic character of the type.

Common Name	Common Description	Relative Condition	Points	Hectares	%Points	%Area	Most Abundant Region
Row Crops	This type includes all cropland where fields are fallow for some portion of the year. Some fields may rotate into and out of cultivation frequently, and year-round cover crops and tame hay fields are generally mapped as grassland.	N/A	418	7,471,620	3.12%	10.80%	High Plains, Central Rolling Plains, Blackland Prairie, Coastal Prairie
Native Invasive: Mesquite Shrubland	Mesquite is most often the dominant species of this broadly defined system, which occurs throughout most of the state, except in east and south Texas. It is typically mapped on former prairie or savanna soils. Codominants vary by region, but lotebush, juniper, sugar or netleaf hackberry, pricklypear species, and agarito are common associated species.	5	774	4,231,343	5.78%	6.12%	Rolling Plains and more sparsely in regions to the SE, extending to the Gulf Coast
Rolling Plains: Mixedgrass Prairie	This type circumscribes a variety of grasslands across a relatively large area and under various past and current management regimes, and mesquite is often an important woody component. Dry sites to the west often contain short grasses such as tobosa, purple threeawn, and buffalograss together with mesquite and succulents such as Engelmann pricklypear and Arkansas yucca. Wetter sties to the east may contain mid-grasses such as little bluestem, sideoats grama, Texas wintergrass, and tall grasses such as Indiangrass and big bluestem in locally well-watered areas. Grazing-tolerant species such as Japanese brome, rescuegrass, and prairie broomweed are common in the modern landscape. Some recently retired cropland fields are also mapped within this type.	3	646	2,921,720	4.83%	4.23%	Eastern Rolling Plains, Canadian River Valley in High Plains
Post Oak Savanna: Savanna Grassland	A variety of grasslands are circumscribed within this type, and disturbance or tame grasses such as Bermudagrass, King Ranch bluestem, kleingrass and bahiagrass (east) are common dominants. Little bluestem, Indiangrass, silver bluestem, Texas wintergrass, tall dropseed, and brownseed paspalum are native species that may be important. Common broomweed, western ragweed, and hog croton are common weedy herbaceous species. Post oak, mesquite, eastern redcedar, blackjack oak, water oak, and yaupon are common woody species and may form sparse woodlands or shrublands in some areas.	4	406	2,306,721	3.03%	3.34%	Post Oak Savanna

Table 5. Twenty-five mapped types made up >1% of the land area of Texas, and together account for 61.9% of the total land area of the state. Relative condition (1 to 5) indicates how closely the current mapped type retains the historic character of the type (continued).

Common Name	Common Description	Relative Condition	Points	Hectares	%Points	%Area	Most Abundant Region
CRP / Other Improved Grassland	This type is mapped primarily over Common Land Unit polygons (field boundaries) with grassland cover within cropland landscapes. They may consist of introduced species such as Mediterranean love grass, weeping love grass, or King Ranch bluestem, or of planted native species such as little bluestem, buffalograss, and sideoats grama.	5	700	1,881,375	5.23%	2.72%	High Plains
Edwards Plateau: Savanna Grassland	Grassland condition varies for this mapped type, but many areas contain non-native King Ranch bluestem as an important species, and Bermudagrass is also frequent. Common native grasses include little bluestem, sideoats grama, silver bluestem, Texas wintergrass, purple three-awn, and common curlymesquite. Trees and shrubs are usually present, and may include plateau live oak,Ashe juniper, mesquite, agarito, and/or cedar elm.	2	389	1,877,860	2.91%	2.72%	Central and Eastern Edwards Plateau, Grand Prairie (Fort Worth Prairie)
Blackland Prairie: Disturbance or Tame Grassland	This type includes grasslands in many conditions, and introduced grasses such as Bermudagrass and King Ranch bluestem are the most frequent dominant species. Shrubs or trees such as mesquite, cedar elm, eastern redcedar, sugar hackberry, and huisache may be present, but typically have low cover.	5	319	1,711,128	2.38%	2.47%	Blackland Prairie, Fayette Prairie
Pineywoods: Pine Forest or Plantation	Managed loblolly pine plantations and forests predominate within this mapped type, and species such as sweetgum, eastern redcedar, yaupon, southern red oak, white oak, water oak, live oak (south), and post oak are common but less dominant components. Shortleaf pine is also common, especially to the north or on drier sties, and longleaf pine may be dominant in limited areas within the range of this species (southeast). Yaupon, American beautyberry, winged elm, and wax-myrtle are common shrub components.	4	295	1,672,851	2.20%	2.42%	South Central Pineywoods
South Texas: Clayey Mesquite Mixed Shrubland	A discontinuous canopy of shrubs and small trees characterize this type, and soils range from clayey to loamy. Species such as mesquite, blackbrush, huisache, granjeno, sugar hackberry, brasil, guajillo, blackbrush, lotebush, pricklypear, and whitebrush are common components. Buffelgrass is a common herbaceous dominant.	3	265	1,613,201	1.98%	2.33%	Western South Texas Plains

Table 5. Twenty-five mapped types made up >1% of the land area of Texas, and together account for 61.9% of the total land area of the state. Relative condition (1 to 5) indicates how closely the current mapped type retains the historic character of the type (continued).

Common Name	Common Description	Relative Condition	Points	Hectares	%Points	%Area	Most Abundant Region
Urban Low Intensity	This type includes areas that are built-up but not entirely covered by impervious cover, and includes most of the non-industrial areas within cities and towns.	N/A	89	1,499,889	0.66%	2.17%	Houston, I-35 Corridor Dallas to San Antonio
Trans-Pecos: Creosotebush Scrub	This type is mapped at low elevations within intermountain basins in the Trans-Pecos, mainly on flats or gently rolling landscapes over gravelly colluvial or alluvial soils. Creosotebush is often the primary dominant, and diversity may be low. Other woody species may include mesquite, mariola, catclaw acacia, and whitethorn acacia. Common succulents include Christmas cactus, Torrey's yucca, Engelmann pricklypear, lechuguilla, and Opuntia species. Bush muhly, fluffgrass, burrograss, slim tridens, threeawns, and chino grama are common grasses.	5	176	1,348,683	1.31%	1.95%	Low Elevations in Trans-Pecos
Gulf Coast: Coastal Prairie	A variety of grasslands are circumscribed by this mapped type, and species such as Bermudagrass, King Ranch bluestem, bahiagrass, deep-rooted sedge, rat-tail smutgrass, broomsedge bluestem, little bluestem, bushy bluestem, and brownseed paspalum may be dominant. Live oak, cedar elm, sugar hackberry, and water oak (east) are common tree components, and shrubs such as huisache, Macartney rose, mesquite, baccharis, or Chinese tallow may be present.	3	291	1,277,632	2.17%	1.85%	Central Coastal Bend
Edwards Plateau: Ashe Juniper-Live Oak Shrubland	Ashe juniper and plateau live oak are the most frequent dominants of this evergreen shrubland. Plateau live oak and/or Ashe juniper may form a sparse canopy and Vasey oak (west), white shin oak, Mohr's shin oak (west), agarito, Texas persimmon, Texas mountain-laurel, mesquite, Lindheimer's pricklypear may be common in the understory.	3	284	1,268,470	2.12%	1.83%	West Central Edwards Plateau
Open Water	Areas that were water year-round at the time of data collection (circa 2010) are included. This includes reservoirs, rivers, canals, ponds, and marine waters along the Gulf of Mexico are also mapped.	N/A	30	1,235,868	0.22%	1.79%	East Texas Reservoirs

Table 5. Twenty-five mapped types made up >1% of the land area of Texas, and together account for 61.9% of the total land area of the state. Relative condition (1 to 5) indicates how closely the current mapped type retains the historic character of the type (continued).

Common Name	Common Description	Relative Condition	Points	Hectares	%Points	%Area	Most Abundant Region
Post Oak Savanna: Post Oak Motte and Woodland	Post oak is the most frequent dominant tree species within this mapped type. Cedar elm, blackjack oak, sugar hackberry, water oak, southern red oak (east), black hickory, and plateau live oak may all be present in the overstory. Mesquite (west), yaupon, common persimmon, possumhaw, winged elm, gum bumelia, American beautyberry, and eastern redcedar are common shrubs.	3	361	1,232,390	2.70%	1.78%	Post Oak Savanna; linear belts formed by geologic outcrops
Pineywoods: Upland Hardwood Forest	Hardwoods such as sweetgum, post oak, southern red oak, and water oak may be dominant within this mapped type, and loblolly pine or shortleaf pine are common components. Slightly wetter sites may contain species such as white oak and willow oak as important overstory trees.	4	97	1,125,284	0.72%	1.63%	Northwestern and Western Pineywoods
High Plains: Shortgrass Prairie	Buffalograss, blue grama, tobosa, and silver bluestem are common dominant grasses of this type. Other grasses may include hairy grama, sideoats grama, western wheatgrass, and purple threeawn. Broom snakeweed, mesquite, lotebush, wolfberry, pricklypear, and sand sage are common woody components.	3	321	1,110,620	2.40%	1.61%	Northern High Plains, Canadian River Valley
Crosstimbers: Savanna Grassland	This type includes grassland in many different conditions, including areas dominated by non-native Bermudagrass and King Ranch bluestem with grazing-tolerant forbs such as broomweed and western ragweed, as well as areas with native species such as little bluestem, Texas wintergrass, Indiangrass, silver bluestem, and sideoats grama. Mesquite is a common shrub, and this mapped type may include some areas with fairly dense mesquite cover.	3	223	1,093,903	1.67%	1.58%	Crosstimbers
Pineywoods: Disturbance or Tame Grassland	This mapped type includes many areas dominated by introduced species such as Bermudagrass, bahiagrass, and Johnsongrass. Important components may also include little bluestem, broomsedge bluestem, and hog croton. Woody species that may be present, but not with significant cover, include loblolly pine, eastern redcedar, yaupon, and post oak.	5	75	1,003,326	0.56%	1.45%	Pineywoods

Table 5. Twenty-five mapped types made up >1% of the land area of Texas, and together account for 61.9% of the total land area of the state. Relative condition (1 to 5) indicates how closely the current mapped type retains the historic character of the type (continued).

Common Name	Common Description	Relative Condition	Points	Hectares	%Points	%Area	Most Abundant Region
Trans-Pecos: Mixed Desert Shrubland	This type is mapped on moderate slopes, usually in hills and low mountains rather than alluvial or colluvial desert basins. Shrub diversity is often relatively high, and common components include mariola, creosotebush, cenizo, guajillo, whitethorn acacia, skeleton-leaf golden eye, mesquite, catclaw acacia, Torrey's yucca, lechuguilla, sotol, pricklypear species, and ocotillo. To the south, species such as cenizo, guajillo, and blackbrush may be important.	1	155	888,484	1.16%	1.28%	Eastern and Southern Trans-Pecos
Trans-Pecos: Hill and Foothill Grassland	This type is mapped over gravelly or rocky, generally sloping soils that are not continuous and thus support a mixture of grasses, shrubs, and succulents. Important grasses may include sideoats grama, black grama, chino grama, tanglehead, threeawns, bush muhly, Arizona cottontop, and fluffgrass. Common shrubs include ocotillo, creosotebush, mariola, skeleton-leaf golden eye, and whitethorn acacia. Common succulents include Torrey's yucca, lechuguilla, sotol, Texas sacahuista, Engelmann pricklypear, and other Opuntia and Echinocereus (small, ribbed cacti) species.	3	117	879,780	0.87%	1.27%	Northern Trans-Pecos
South Texas: Sandy Mesquite Woodland and Shrubland	Relatively dense mesquite low woodlands are characteristic of this type. Shrub composition varies and diversity may be relatively high, and granjeno, blackbrush, Texas hogplum, brasil, colima, huisache, Texas persimmon, and whitebrush may be components. Overstory canopy is often sparse and contains species such as mesquite, huisache, Texas ebony, and plateau live oak.	3	207	868,473	1.55%	1.26%	Eastern South Texas Plains
South Texas: Disturbance Grassland	A variety of mainly heavily grazed grasslands, including managed exotic pastures, are circumscribed within this type. Grasses and shrubs both are important components. Common dominant species include buffelgrass, Bermudagrass, King Ranch bluestem, Kleberg bluestem, guineagrass, pink pappusgrass, threeawn species, and red grama. Shrubs and small trees may include mesquite, huisache, blackbrush, lotebush, huisachillo, and granjeno.	5	155	823,179	1.16%	1.19%	Eastern South Texas Plains; Rio Grande Delta

Table 5. Twenty-five mapped types made up >1% of the land area of Texas, and together account for 61.9% of the total land area of the state. Relative condition (1 to 5) indicates how closely the current mapped type retains the historic character of the type (continued).

Common Name	Common Description	Relative Condition	Points	Hectares	%Points	%Area	Most Abundant Region
Edwards Plateau: Live Oak Motte and Woodland	Plateau live oak alone or with Ashe juniper usually dominates the overstory of this type. Deciduous trees such as cedar elm, sugar hackberry, white shin (or Vasey) oak, Lacey oak, and Texas oak may be components. Shrubs such as mesquite, Texas persimmon, and agarito are common.	3	165	760,740	1.23%	1.10%	Central Edwards Plateau
Edwards Plateau: Juniper Semi-arid Shrubland	Redberry juniper and Ashe juniper may both be present in this type, together with species such as plateau live oak, mesquite, Texas persimmon, Lindheimer pricklypear, Texas sotol, and agarito. Important grasses may include sideoats grama, purple threeawn, curlymesquite, slim tridens, hairy tridens, and Texas wintergrass.	1	105	697,806	0.78%	1.01%	Western Edwards Plateau

Selection of mapped types that are of conservation concern is fraught with uncertainly. Many of the mapped types cover relatively small areas and contain few sample points, so the overall accuracy of mapping is difficult to determine. Plant communities, and thus mapped types, represent recognizable units, but these shift over time under constantly changing conditions. Many floodplain and riparian types are either similar to each other, or are similar to surrounding upland types in the modern landscape. Nonetheless, we selected 21 (non-wetland, non-floodplain) types that are worthy of recognition (Table 6). These types are generally rather unique within that region where they occur, either at a very local or a larger resolution. Many harbor rare flora or fauna, and some are tied to unusual geophysical settings.

Table 6. Selected regionally unique mapped types in Texas.

Representative Type	Type Common Description	Hectares	%Area	Type Comments
Chenier Plain: Live Oak Fringe Forest	Nearly pure stands of coastal live may occur within this mapped type, and species such as sugar hackberry, western soapberry, Carolina laurelcherry, and Hercules-club pricklyash may be present. Loblolly pine may also be a component.	409.38	0.0006%	Live oak types extend from Louisiana to the Coastal Sand Plain, and include related live oak woodlands in the southern Post Oak Savanna
Coastal and Sandsheet: Deep Sand Grassland	Seacoast bluestem. rat-tail smutgrass, three-awns, and gulfdune paspalum are often important in this mapped type, especially coastward, and tanglehead grass dominates some more inland areas. Slightly lower areas may be dominated by marshhay cordgrass or gulf cordgrass.	599,039.88	0.8663%	The Coastal Sand Plain is a large, relatively intact landscape with live oak, shrubland, and wetland types
Columbia Bottomlands: Hardwood Forest and Woodland	This type includes a wide variety of successional and more mature forests as well as encompassing wetter and drier sties. Common species include water oak, sugar hackberry, cedar elm, green ash, pecan, live oak, Shumard oak and American elm. Yaupon is a common understory shrub and dwarf palmetto is common on wetter sites.	170,106.47	0.2460%	The Columbia Bottomlands is a large woodland/forest complex that bisects the Upper Coastal Prairie along the Brazos and San Bernard Rivers
Edwards Plateau: Oak - Ashe Juniper Slope Forest	Deciduous oaks such as Texas oak, Lacey oak (west), white shin oak, and chinkapin oak share dominance with Ashe juniper in this mixed woodland or forest, and plateau live oak is often a component. Other deciduous trees such as cedar elm, netleaf hackberry, escarpment black cherry, and Arizona walnut may be in the canopy. Understory species may include red buckeye, Texas redbud, and roughleaf dogwood, along with Ashe juniper.	104,615.39	0.1513%	Heavily dissected areas of the Balcones Canyonlands and river breaks flowing off the Edwards Plateau toward the south and east form large, wooded landscape patches with a number of rare species
Grand Prairie: Tallgrass Prairie	Little bluestem and King Ranch bluestem are common dominants of this mapped type in the modern landscape, depending on grazing pressure. Other important species may include silver bluestem, sideoats grams, big bluestem, Indiangrass, and tall dropseed. Mesquite, sugar hackberry, plateau live oak, cedar elm, or Ashe juniper may form a shrub or sparse tree canopy cover.	187,654.99	0.2714%	This is the largest remaining unplowed patch of unbroken tallgrass prairie sod remaining in Texas
Pineywoods: Catahoula Herbaceous Barrens	This mapped type occurs over soils that may vary in depth across small areas. Important species, depending on soil depth, may include Nuttall's rayless golden-rod, poverty dropseed, poverty threeawn, little bluestem, broomsedge bluestem, and Silveus' dropseed. Post oak, blackjack oak, and pines (longleaf, loblolly, or shortleaf) may form a sparse overstory.	35.90	0.0001%	A rare type that provides habitat to a number of rare plant species

Table 6. Selected regionally unique mapped types in Texas (continued).

Representative Type	Type Common Description	Hectares	%Area	Type Comments
Pineywoods: Hardwood Flatwoods	Southern red oak, willow oak, water oak, laurel oak, swamp chestnut oak (east), overcup oak, sweetgum, winged elm, and green ash are common components of this mapped type. Loblolly pine or longleaf pine (south) may be components and dwarf palmetto may form an understory, but is absent in the north. Some areas in the south are locally dominated by Chinese tallow. Winged elm, American beautyberry, yaupon, possumhaw, and wax-myrtle are often present in the understory.	148,692.22	0.2150%	A large complex of flatwoods extends inland from the Upper Coastal Prairie east of Houston, and includes portions of the "Big Thicket"
Pineywoods: Southern Mesic Hardwood Forest	Relatively steep slopes and narrow valleys or ravines characterize this mapped type. White oak, blackgum, sweetgum, southern red oak, water oak, willow oak, mockernut hickory, and red maple are common components. In the wettest areas in the south, southern magnolia and American beech may be locally dominant. American hornbeam, American holly, and American hop-hornbeam are common understory components.	27,206.79	0.0393%	Both southern and northern mesic ravines and creek bottoms support rare plant species and unique, mesic hardwood or mixed hardwood/pine forests
Pineywoods: Weches Herbaceous Glade	This mapped type consists of herbaceous vegetation that may occur over relatively shallow to relatively deeper soils. Grasses such as Bermudagrass, three-awns, hairy grama, Texas grama, little bluestem, and broomsedge bluestem are common components. Shrubs and scattered trees such as eastern redbud, gum bumelia, roughleaf dogwood, eastern redcedar, post oak, and loblolly pine may be present. The shallowest soils may be dominated by species such as poverty dropseed, Texas sedum, and Ozark savory.	3,380.17	0.0049%	Rare type that provides habitat to a number of rare plant species
Post Oak Savanna: Sandyland Grassland	Little bluestem and brownseed paspalum are common dominants of this type, together with a variety of grasses and forbs common on sands, including curly three-awn, bluntsepal Brazoria, Illinois flatsedge, Florida snake-cotton, purple sandgrass, and pinweed. Post oak, blackjack oak, bluejack oak, black hickory, and sand post oak may be present.	5,102.44	0.0074%	Deep sandy soils support woodlands and grasslands with unique and rare plant species that often apparently retain a fairly natural character
Rio Grande Delta: Evergreen Thorn Woodland and Shrubland	This type is mapped primarily on bottomland soils and dominated by evergreen trees such as Texas ebony and anacua. A wide diversity of shrubs and low trees may occur, including mesquite, la coma, sugar hackberry, cedar elm, granjeno, Texas persimmon, tepeguaje, snake-eyes, torchwood, colima, brasil, guayacan, and desert olive. Currently, guineagrass is a conspicuous herbaceous element in many occurrences.	2,215.79	0.0032%	Small remnants of evergreen thorn woodlands provide habitat to a number of southern plant and animal species that are rare in Texas

Table 6. Selected regionally unique mapped types in Texas (continued).

Representative Type	Type Common Description	Hectares	%Area	Type Comments
Rolling Plains: Breaks Deciduous Shrubland	This type extends from drier sites with more low shrubs in the west to more moist sites with fewer shrubs in the east. Examples tend to be quite diverse with a relatively diverse compliment of native shrubs and herbaceous species. Common shrubs include mesquite, redberry juniper, joint-fir, lotebush, feather dalea, littleleaf sumac, and catclaw acacia. Common herbaceous species include purple threeawn, sideoats grama, sand dropseed, tobosa, Texas wintergrass, prairie broomweed, blue grama, little bluestem, and silver bluestem.	471,162.16	0.6813%	Slope complexes include a number of types, some with gyp outcrops and inclusions; these areas are relatively intact landscapes with diverse plant communities that appear to retain a fairly natural character
South Texas: Loma Evergreen Shrubland	These mainly low, relatively dense shrublands occur over both slightly saline and non-saline soils. A diversity of shrubs may be important, including species such as mesquite, Spanish dagger, blackbrush, screwbean mesquite, Lindheimer pricklypear, Berlandier's fiddlewood, Texas ebony, gutta-percha, colima, brasil, and huisachillo. Grasses such as big sacaton, buffelgrass, and gulf cordgrass may be present.	7,084.30	0.0102%	Lomas are uncommon and have unique plant communities, some with more southern and/or more salt-tolerant plant species
South Texas: Salty Thornscrub	This type may be over more or less salty soils, and often contains mesquite as the overstory dominant except on the saltiest sites. A variety of shrubs and succulents may be present, including species such as blackbrush, amargosa, lotebush, palo verde, leatherstem, guayacan, granjeno, tornillo, goldenweed, Lindheimer pricklypear, tasajillo, four-wing saltbush, and saladillo. Buffelgrass, red grama, Kleberg bluestem, curlymesquite, and whorled dropseed are common grasses.	112,655.34	0.1629%	Salty-influenced landscapes with unique plant species composition form fairly large patches with a diversity of plant communities that vary due to salinity and drainage
South Texas: Shallow Shrubland	A more or less discontinuous canopy of shrubs and small trees characterize this type, and species such as mesquite, guajillo, blackbrush, cenizo, granjeno, Texas persimmon, guayacan, leatherstem, Texas kidneywood, and colima are common components. Succulents such as yucca species, sotol, Lindheimer cactus, and tasajillo are important on some sites.	642,654.35	0.9293%	This type includes slopes and shallow flats that are often more open, lower in stature, and more diverse than more extensive, deep-soiled shrublands
Trans-Pecos: Desert Deep Sand and Dune Shrubland	This type is mapped over deep desert sands mainly in the far western part of the Trans-Pecos. Species such as mesquite, sand sage, and soaptree yucca are common dominants. Diversity of associated grasses and forbs may be high, with species such as sand dropseed, mesa dropseed, giant dropseed, black grama, broom pea, grassland croton, and spectaclepod common.	95,698.18	0.1384%	Extensive dunes are found within the Hueco and Salt Basins of West Texas, and these occur as active sand dunes as well as sand hills stabilized by shrublands and grasslands
Trans-Pecos: Gyp Dune	This type is mainly mapped over sandy soils in the gyp-influenced area in the vicinity of the Guadalupe Mountains, and includes both barren and vegetated, stabilized dunes. Important species may include gypgrass, gyp grama, rough coldenia, sand sage, broom pea, hoary rosemary-mint, wooly dalea, sand bluestem, giant dropseed, and Indian ricegrass.	4,304.78	0.0062%	These unique gyp-dominated dunelands are found within the Salt Basin west of the Guadalupe Mountains, and harbor unique associated flora and fauna

Table 6. Selected regionally unique mapped types in Texas (continued.)

Representative Type	Type Common Description	Hectares	%Area	Type Comments
Trans-Pecos: Loamy Plains Grassland	This type is mapped over relatively deep, loamy soils, often in areas within a matrix of broad grasslands over shallower soils (Trans-Pecos: Shallow Desert Grassland) or more rolling, discontinuous soils (Trans-Pecos: Desert Grassland). Important grasses may include sideoats grama, black grama, blue grama, hairy grama, tobosa, silver bluestem, and fluffgrass. Mesquite is a common invasive species, along with tarbush and creosotebush, but these areas generally lack javelina bush, whitethorn acacia, or juniper species in much density.	579,389.67	0.8378%	In conjunction with the Trans-Pecos: Shallow Plains Grasslands, these grasslands occur as a significant grassland landscape (the Marfa Grasslands) in southern Jeff Davis and adjacent northern Presidio Counties
Trans-Pecos: Montane Mesic and Canyon Hardwood - Pine - Juniper Forest	This type is mapped mainly in canyons along streams, and may represent communities on a variety of substrates and under different moisture regimes. Species composition varies among the mountain ranges (Guadalupes, Davis, and Chisos). Common components include ponderosa or Arizona pine, pinyon or Mexican pinyon pine, alligator juniper, gray oak, Emory oak, Chisos red oak, Texas madrone, chinkapin oak, bigtooth maple, and southwestern chokecherry.	4,446.15	0.0064%	These woodlands harbor a diversity of deciduous and evergreen tree species that occupy moderate to high elevations in the mountains of West Texas. Structural diversity and mesic conditions provide habitat for numerous rare species
Trans-Pecos: Succulent Desert Scrub	This type is mapped at low elevations on relatively steep slopes. Shrub, succulent, and grass diversity is often relatively high though vegetative cover may be low. Succulents may include species such as Torrey’s yucca, Texas sotol, lechuguilla, pricklypear species, and candelilla. Shrubs such as ocotillo, creosotebush, mariola, whitethorn acacia, leatherstem, skeleton-leaf golden eye, mesquite, and desert olive are common. Grasses may include species such as chino grama, black grama, sideoats grama, slim tridens, and threeawns.	370,473.06	0.5357%	This type provides habitat for numerous rare and usual plant species.

Noteworthy Improvements Over Past Maps

We mapped 398 types statewide at 10 m spatial resolution. Aside from the large number of types mapped and improved spatial resolution, a number of general improvements in mapping applied statewide, including:

(1) the mapping of live oak-dominated communities , which are major elements of the landscape from the Gulf Coast northward and northwest into Central Texas,

(2) the mapping of slope forest types, which are especially extensive in Central and West Texas,

(3) the mapping of floodplain and riparian communities,

(4) the mapping of a wide variety of disturbance type shrublands and woodlands throughout the state, and

(5) the mapping of a wide variety of types that are associated with unique soils, especially deep sands, salty, and gyp-influenced soils.

In addition, a number of improvements applied mainly to a specific phase of the project.

Phase 1

(1) the mapping of pines versus junipers in the Bastrop Lost Pines region,

(2) the mapping of slope forest and shrubland communities in the Balcones Canyonlands region,

(3) the mapping of Llano Uplift communities, and

(4) the mapping of non-calcareous community types versus calcareous types over limestone

Phase 2

(1) the mapping of temporary and seasonally flooded bottomland types,

(2) the mapping of flatwoods types,

(3) the mapping of dry “ridge” types in the Pineywoods,

(4) the mapping of sandylands and sandhill types, both in the Post Oak Savanna and the Pineywoods,

(5) the mapping of Catahoula Barrens and Weches Glades, and

(6) the mapping of mesic ravine types in the Pineywoods.

Phase 3

(1) the mapping of Columbia Bottomlands types on the upper coast,

(2) the mapping of Coastal Sandsheet types (Phase 3 and Phase 4),

(3) the mapping of live oak types in the Post Oak Savanna, on the Coastal Sand Sheet, and in portions of the Coastal Prairie,

(4) the mapping of algal flats and wind tidal flats,

(5) the mapping of loma types, and

(6) the mapping of saline lakebed and fresh pond and laguna types.

Phase 4

(1) the mapping of a variety of different shrubland and associated types based on soils: sandy, clayey, shallow, and salty,

(2) the mapping of Coastal Sandsheet types (Phase 3 and Phase 4), including recognition of outlier sand sheet types in Phase 4,

(3) the mapping of South Texas shrubland types as they intergrade with Post Oak Savanna, Blackland Prairie, and Coastal Prairie types to the north and east,

(4) the mapping of South Texas shrubland types as they intergrade with Edwards Plateau and Trans-Pecos types to the north and west, and

(5) the mapping of Rio Grande Delta shrubland types.

Phase 5

(1) the mapping of a variety of different desert shrublands on broadly-distributed soils and landforms: creosote, mixed desert shrubland, and succulent desert shrubland,

(2) the mapping of more localized types: gyp-influenced, sand-influenced, badland, and volcanic types,

(3) the mapping of a variety of grassland types at low to moderate elevation: loamy plains, shallow plains, sandy, and clay flat,

(4) the mapping of oak versus juniper types in low elevation mountains,

(5) the mapping of mountain types based on elevation and landform: canyon, steep slope, and high elevation, and

(6) the mapping of desert wetland cienega types.

Phase 6

(1) the mapping of outliers of the Edwards Plateau and High Plains communities in the Rolling Plains,

(2) the mapping of breaks types that clearly show the location and influence of river hills,

(3) the mapping of gyp breaks types, and

(5) the mapping of dune and sandhill types associated with river deposits in the Rolling Plains.

Phase 7

(1) the mapping of dune and sandhill types on the High Plains,

(2) the mapping of saline lake and playa types, and

(3) the mapping of the current extent of Conservation Reserve Program grasslands on the High Plains.

Final Map and Database Production

Initial data delivery (for the first development of Phase 1) was as a 10 m raster product. Subsequently (including for the second development of Phase 1), we delivered the data in vector format within a file geodatabase. The Texas Parks & Wildlife Department will lead on making data sets and interpretative materials available in the future. Their efforts include plans to provide web access to selected sets of maps and interpretive materials, with an eye toward use within a planning and management context.

Development of Interpretive Materials

We developed interpretive guides for each phase of the project. These summaries included (1) brief, one to several sentence descriptions of the mapped types directed toward a general audience for use with the map; (2) longer, technical descriptions of most mapped ecological system types that include more details and focus most on later successional (higher-quality) plant communities, (3) photos of mapped types from the field sampling, and (4) notes on where mapped types can be viewed on public lands. New statewide range maps that depict the overall relative density of each mapped type were generated. The original phase-by-phase documents are available from the Texas Parks & Wildlife Department.

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Appendix 1. Field Data Collection Notes

Phase 1

Data Collection: October 2007 to October 2008
Total Field Days: 78
Total Number of Sites: 2900
Average Sites/Day: 37

All data were collected via roadsides or public lands. Points were clustered around Bastrop, TX in an effort to map the extent of the Loblolly pine plant communities.

Phase 2

Data Collection: September 2008 to May 2009
Total Field Days: 79
Total Number of Sites: 1875
Average Sites/Day: 24

The dense nature of the forest vegetation in Phase 2 (West Gulf Coastal Plain) made visibility difficult and accuracy of species identification from the roadside varied. In order to minimize this problem, as well as access sensitive/unique forest sites, efforts were made to access public land and cooperate with private land owners to gain access. Also, data collection in the coastal portion of Phase 2 was impacted by Hurricane Ike and an unusually dry post hurricane period. Some marsh sites were revisited after the plant community had recovered to confirm the accuracy of species identification and system classification. Additional data points were collected in the historic range of longleaf-pine communities in an effort to differentiate these communities from other pine types.

Phase 3

Total Field Days: 84
Total Number of Sites: 2112
Average Sites/Day: 25

A high percentage of field sites were located on private land due to the decreased availability of public lands and increased cooperation of landowners, field biologists, and land managers. We emphasized characterizing and distinguishing among riparian types. Field data points where occasionally clustered around riparian/floodplain zones, predominantly in the Coastal Bend region of Texas. Higher than normal temperatures and less than average rainfall contributed to significant drought conditions during the summer of 2009, making field data collection in the grasslands of the coastal prairie challenging.

Phase 4

Data Collection: July 2009, and January 2010 to April 2011
Total Field Days: 78
Total Number of Sites: 1824
Average Sites/Day: 23

As in Phase 3, many field data collection sites were located on private land with access facilitated by local TPWD biologists, land managers, and property owners. In areas of dense shrubland, documentation of herbaceous vegetation was difficult. Also, the spring of 2011 marked the beginnings of a record-setting drought and wildfire season in Texas making plant identification at the end of this phase difficult.

Phase 5

Data Collection: June 2010, and March 2011 to March 2012
Total Field Days: 85
Total Number of Sites: 1769
Average Sites/Day: 21

Due the small number of public roads and properties in the Trans Pecos, field data collection in Phase 5 relied on cooperation with local TPWD biologists and land owners. The rugged landscape also required data collection sites that were, to some extent, clustered. To the extent possible, samples were selected to represent community change along elevation gradients in mountains. Variation in geologic formation was also captured within the sampling strata. Some field data collected for this phase is only available for project use and is not in the public database. Texas' extreme drought and active wildfire season continued throughout this sampling period. Previous vegetation reports (when available) and local experts were consulted to try to overcome this issue. Extra data were collected to document burned areas.

Esteban Muldavin of New Mexico State University and Helen Poulos of Weslyan University graciously provided input for Phase 5. Dr. Muldavin provided plot data and classification work he and co-workers have done in the Guadalupe and Davis Mountains. Dr. Poulos provided plot data and classification from work she has done in the Davis and Chisos Mountains.

Phase 6

Data Collection: March 2012 and August 2012
Total Field Days: 56
Total Number of Sites: 1712
Average Sites/Day: 30

With the cooperation of landowners and managers, data collection continued on private lands. However, an improved road network versus Phase 5 allowed for a larger number of roadside field sample sites. While some areas of Phase 6 received rainfall prior to sampling, most of this region had not recovered from severe drought conditions experiences in the year or more previous to sampling. Identification of perennial grasses was problematic at many sites. As with Phase 5, additional data regarding burn severity and recovery was sometimes collected.