United States Department of Agriculture

Light Detection and Ranging (LiDAR) for Improved Mapping of Wetland Resources and Assessment of Wetland Conservation Practices

Natural Resources Conservation Service
Conservation Effects Assessment Project

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Summary Findings

LiDAR elevation data can be used to map the potential, static distribution of current and historic wetlands and key wetland functional drivers based on physical controls on water distribution. LiDAR intensity data can be used to map actual, dynamic variations in wetland inundation extent which can provide additional insights concerning key functional drivers.

LiDAR intensity data significantly improved the mapping of inundation below the forest canopy compared with using aerial photography. The accuracy of the LiDAR intensity based wetland inundation map was 97% versus 70% for the aerial photography based map, or about 30% more accurate.

Relief relative to a local elevation maximum provided a strong indicator of inundation dynamics (i.e., hydroperiod), but was less useful for mapping wetland boundaries. Combining local relief and an Enhanced Topographic Wetness Index produced a map that was well suited for mapping wetland extent and hydroperiod. Wetlands mapped using aerial photographs or LiDAR-derived digital elevation models (DEMs) contained a similar amount of inundated area, but the LiDAR-derived maps contained fewer errors of omission. For this reason, it was concluded that DEM based topographic metrics produced enhanced inundation maps relative to aerial photography derived maps.

When using LiDAR derived DEMs our results support the use of more distributed flow routing algorithms over algorithms that force greater flow convergence for the mapping of palustrine wetlands in areas with low topographic gradients. Accounting for water outflow as well as inflow is key to developing robust indicators of water accumulation potential.

A concerted effort is ongoing by NRCS and other federal agencies to hasten the collection of high quality LiDAR data throughout the entire United States and facilitate enhanced analyses of natural resources and ecosystems.

Remotely sensed data have long been an important tool for the assessment of land condition and the effects and effectiveness of land management. The USDA has an extensive history of remotely sensed data use, which has largely focused on aerial photography. Although the inherent benefits of aerial photography and established operational data processing structures merit the continued use of this data stream, newer types of remotely sensed data, including Light Detection and Ranging (LiDAR), have been shown to provide robust, synergistic information on conservation practices when used in conjunction with aerial photography. This includes, but is not limited to, the use of LiDAR data to improve the mapping and characterization of wetlands.

Although U.S. wetlands are currently mapped using aerial photography, these maps are often out of date and errors can be substantial (Stolt and Baker 1995; Kudray and Gale 2000), especially in difficult-to-map areas, which include wetlands with intermittent hydrology and forested wetlands. The Natural Resources Conservation Service (NRCS) is one of several Federal agencies that have expressed the importance of LiDAR data for improved wetland mapping and characterization (Snyder and Lang 2012).

Until recently, the spatial resolution of commonly available digital topographic data for the United States (vertical accuracies of ~3.3–32.8 ft [1–10 m]) was insufficient to map many geomorphologic features, including most wetlands. However, LiDAR-derived digital elevation models (DEMs) provide superior vertical accuracy (~3.9–5.9 in [~10–15 cm] and horizontal resolution (~39.4– 78.7 in [~100–200 cm] [Coren and Sterzai 2006]), allowing the enhanced mapping and characterization of existing, former, and restored wetlands, which can improve the implementation of wetland conservation practices. The use of LiDAR data can be especially vital in areas with low topographic variation, particularly when applied to mapping or monitoring wetlands that have previously been difficult to detect, such as forested wetlands.

This Conservation Effects Assessment Project (CEAP) Science Note briefly introduces discrete point return LiDAR technology, the most readily available type of LiDAR; describes multiple studies that have demonstrated the benefits of this technology for improved wetland mapping and characterization; and discusses the implications of these studies and others for improved wetland mapping and assessment of wetland conservation practices.

Light Detection and Ranging (LiDAR) Technology

LiDAR sensors provide detailed information on the elevation of the Earth's surface and objects on the landscape, such as vegetation and human-made structures. LiDAR sensors collect data through the use of an onboard laser system, which sends and receives laser energy. LiDAR sensors send frequent (hundreds of thousands per second) short pulses of laser energy, and a portion of that energy is reflected back to the sensor where it is recorded. Most LiDAR sensors used for land-based remote sensing operate in the near-infrared region of the electro-magnetic spectrum (commonly in the 0.90 to 1.55 µm wavelength range; Lemmens 2007), with 1.06 µm (near-infrared) being a commonly used laser wavelength (Goodwin et al. 2006). LiDAR data can be used to calculate precise x, y, z locations through the use of a highly accurate onboard Global Positioning and Inertial Navigation System and by calculating the distance to an object by recording the amount of time it takes for a pulse, or a portion of that pulse, to travel from the sensor to the target and back (Goodwin et al. 2006). LiDAR x, y, z points can be used to make DEMs through the interpolation of LiDAR point returns. The resolution of the resultant DEM is based largely upon the original density of LiDAR returns (point density) and user requirements. If only points originating from the Earth's surface, as opposed to points originating from above the Earth's surface (e.g., trees, grass, and buildings) are used for the interpolation, then the resultant image is called a bare earth DEM, and it represents topography. While return time provides information on location, LiDAR intensity, or the strength of the returned LiDAR signal relative to the amount of energy transmitted by the sensor per laser pulse (Chust et al. 2008), provides information regarding the identity of target materials which the LiDAR signal reflects from before returning to the sensor.

Wetland Applications of LiDAR

LiDAR Intensity

LiDAR intensity data are well suited for the identification of inundation, and possibly saturation, due to the strong absorption of near-infrared energy (the energy detected by most terrestrial LiDAR sensors) by water. Information derived from LiDAR intensity is complementary to LiDAR-based information on x, y, z location, and each LiDAR point return contains both types of information. The association of individual points of LiDAR intensity with precise x, y, and z values allows the selection and display of LiDAR intensity originating from the Earth's surface exclusively, in this way reducing the impact of a plant canopy or other vertical structures on the ability to discriminate inundated versus non-inundated areas on the ground. In this way, LiDAR intensity data can be readily filtered to remove the influence of the canopy. On the other hand, aerial photography cannot be similarly filtered and will contain a mix of information from the plant canopy and the ground.

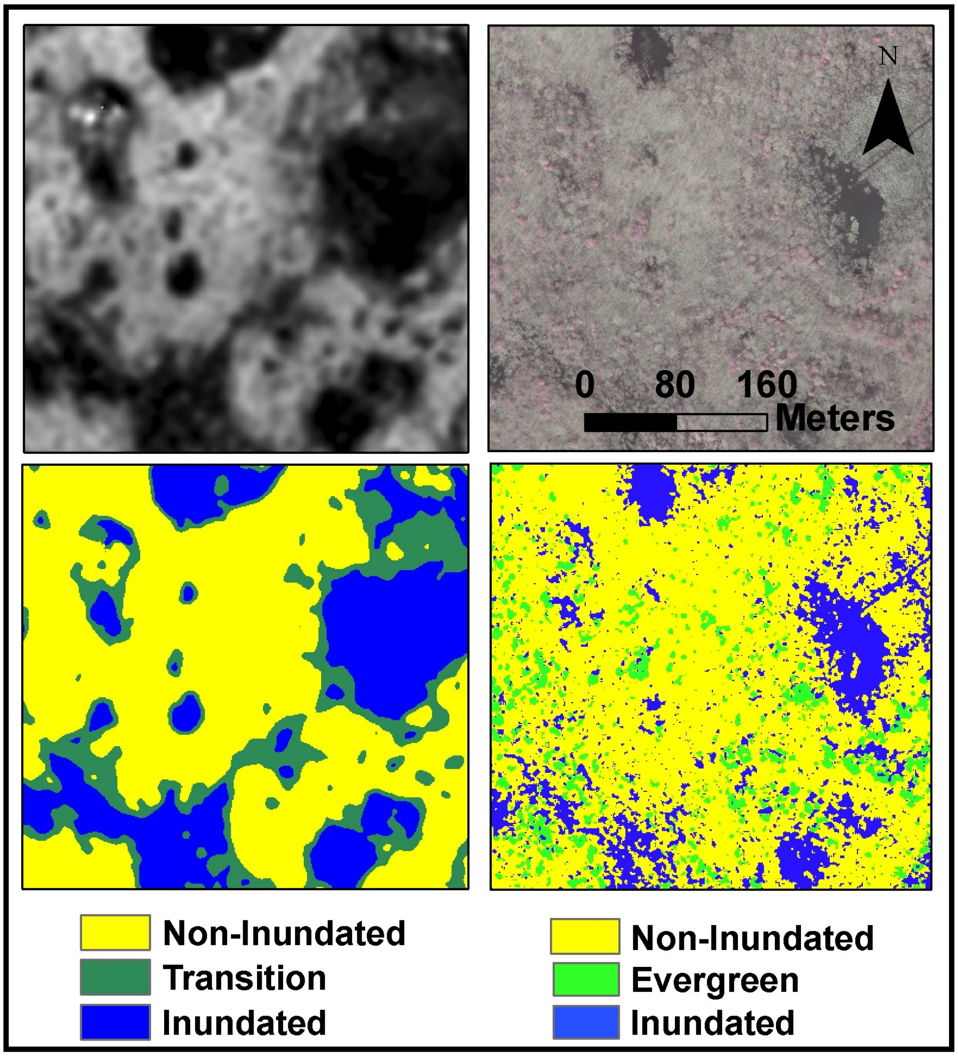
A study was conducted to determine the relative ability of LiDAR intensity and aerial photography to map inundation beneath the forest canopy in the Choptank River Watershed, an agricultural watershed on the Eastern Shore of Maryland (McCarty et al. 2008). Although inundation does not always equate with wetland status, data were collected during maximum hydrologic expression at the beginning of the growing season, March 27, 2007. Therefore, areas that were inundated during the study period were very likely to meet the hydrologic definition of a wetland and although areas that were not inundated during the study period could still meet this definition they were much less likely to do so. The mapping of forested wetlands is particularly important because these are the most common type of wetland in the United States and they are particularly difficult to map using existing technologies, such as aerial photography. This is especially true in areas of low topographic relief, such as the outer Coastal Plain of the Mid-Atlantic. Accurate maps of wetland extent and character are critical for a wide variety of natural resource management activities. For example, they can be used to assess the effects and effectiveness of forested wetland restoration and compare the level of ecosystem services provided by restored and less disturbed wetlands.

To meet the goal outlined above, LiDAR intensity data were collected using an Optech ALTM 3100 LiDAR sensor flown at 2,000 ft (~610 m) above the Earth's surface. Data were collected with a laser pulse frequency of 100,000 pulses of 1.06 µm wavelength energy per second at a scan angle of ± 20^{o} using a scan frequency of 50 Hz and a 12-bit dynamic range. The resultant data had a vertical accuracy of ± 5.91 in (15 cm) and an average bare earth point density of ~0.23 pt ft^{-2} (2.5 pts m^{-2}). The sensor was coupled with a digital camera to capture coincident 4.72 in (12 cm) spatial resolution aerial photography in the near-infrared (0.72–0.92 µm), red (0.60–0.72 µm), and green (0.51–0.60 µm) bands (Lang and McCarty 2009).

The LiDAR intensity data were spatially filtered to reduce noise and a simple thresholding technique was used to create a map of inundation below the forest canopy. Prior to analysis, the aerial photograph was resampled to a spatial resolution of 1 m and an unsupervised isodata classification procedure was used to create a map of inundated and non-inundated forest using all bands of the digital image. The resultant inundation map was filtered to reduce error. The LiDAR intensity and aerial photography-based maps of inundation were validated with ground-based information on inundated and non-inundated areas collected using a highly accurate Trimble GeoXT global positioning system (GPS; Lang and McCarty 2009).

The study found that LiDAR intensity data significantly improved the mapping of inundation below the forest canopy relative to aerial photography (fig. 1). The LiDAR intensity-based inundation map was 97 percent versus 70 percent accurate, respectively or nearly 30 percent more accurate than the aerial photography-based map (Lang and McCarty 2009). Not unexpectedly, evergreen areas were found to influence the accuracy of both maps, although the impact appeared to be much greater on the aerial photography-based map. Tree canopy reflectance and shadow appeared to cause a large portion of the error contained within the aerial photography based-map. Since water is a strong absorber of visible and near-infrared energy, the expected low reflectance of

Figure 1. The original datasets (filtered intensity, top left, and aerial photography, top right) used to produce two different inundation maps (resultant map directly below parent dataset). Note that inundation patterns are more distinct in the LiDAR intensity image and resultant inundation map. Adapted from Lang and McCarty 2009.



water is easily confused with decreased reflectance in areas affected by shadow. Conversely, reflectance off of a tree canopy, even during the leaf-off period, is more similar to reflectance from non-inundated soils and organic debris (Lang and McCarty 2009). These influences are generally absent from or can be removed from LiDAR intensity data.

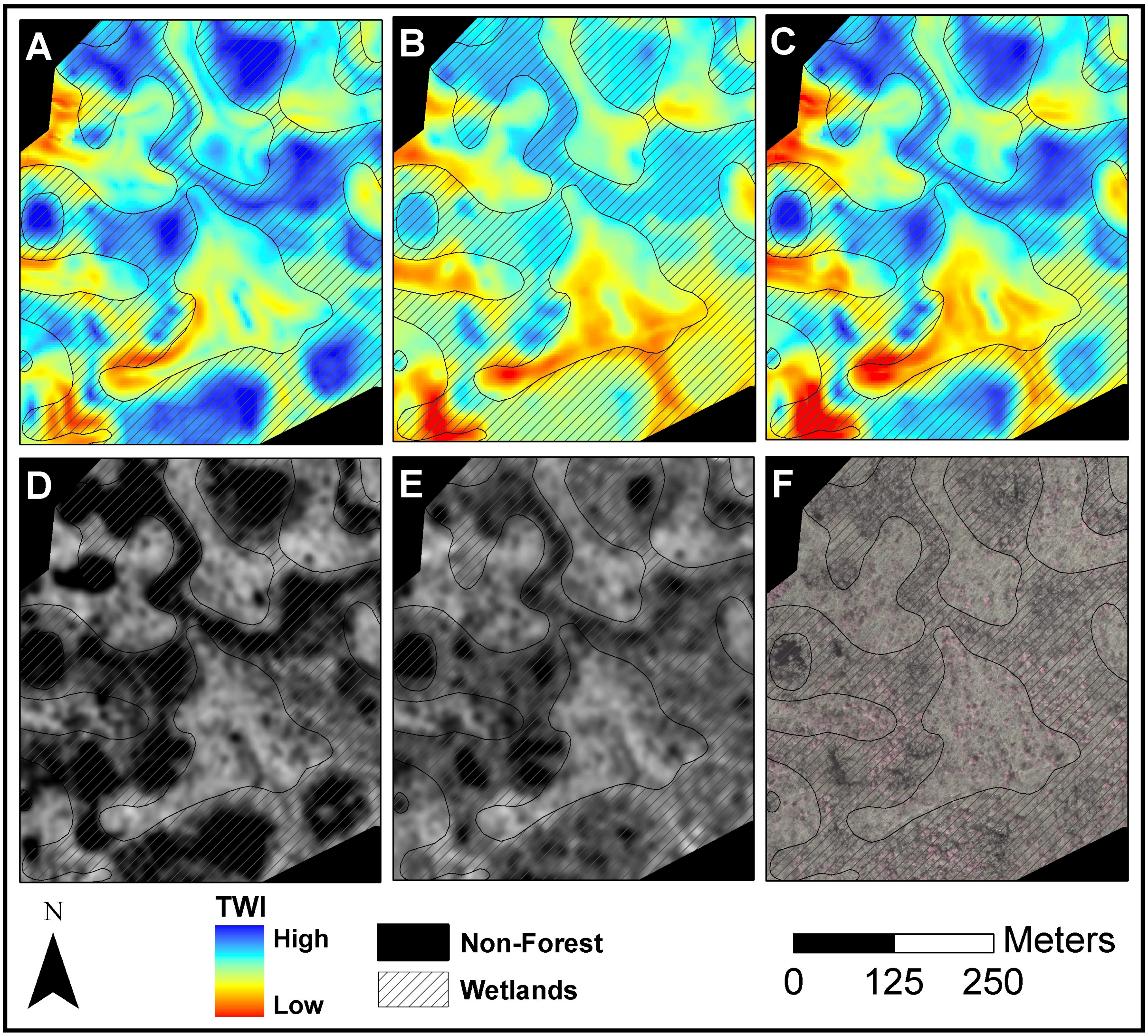
Although largely untapped, the potential of LiDAR intensity data to better understand fundamental ecosystem processes and improve land cover classification is strong. This was the first study to examine the ability of LiDAR intensity to map inundation below the forest canopy. A later study found that LiDAR intensity data have the potential to assist with the relative differentiation of deciduous forests with varying degrees of surface wetness and, therefore, wetland status within the coastal region of North Carolina (Newcomb and Lang 2011), supporting the conclusions drawn by Lang and McCarty (2009). Although there are inherent limitations of LiDAR intensity data, including the fact that the data are typically uncalibrated (i.e., standardized) between LiDAR collections and that they are sensitive to the angle at which the laser interacts with the Earth's surface, these weaknesses can be greatly reduced through the interpretation of LiDAR intensity data within one collection and the use of these data in areas of relatively low topographic variability, such as the Coastal Plain. Furthermore, intensity data are often included with LiDAR elevation data for low or no cost. Therefore, it makes sense to take advantage of this relatively untapped data stream when LiDAR intensity data are well suited for project needs. This statement is particularly relevant given the often limited availability of suitable imagery for wetland mapping and characterization.

LiDAR-Derived Topographic Metrics

DEMs can be used to predict the movement and distribution of water and thus relative wetness across the landscape. Whereas LiDAR intensity detects the presence of water, LiDAR based topographic metrics can predict the potential distribution of water accumulation across the landscape. Multiple types of topographic metrics can be produced using DEMs and used to infer relative wetness. These metrics relate to physical controls on water distribution. For example, the topographic wetness index is a commonly used topographic metric based on slope and contributing area and is expressed as $\ln(\alpha/\tan\beta)$, where α is the upslope contributing area per unit contour and $\tan\beta$ is the local topographic gradient (Beven et al. 1995). Although β has been calculated using a fairly consistent methodology, methods used to calculate α vary considerably based on the applied flow-routing algorithm (Lang et al. 2012). Numerous flow-routing algorithms are available, including the commonly used D8 (distribution of flow to one neighboring cell); the somewhat more distributed D∞ (distribution of flow to 1 or 2 neighboring cells); and FD8, which distributes flow to all neighboring pixels. These algorithms proportion flow according to slope with greater slope leading to increased allocations of water. The following section describes a study that investigated the ability of multiple LiDAR DEM-derived topographic metrics, including three topographic wetness indices computed using different flow routing algorithms, to map wetlands in the Choptank River Watershed on Maryland's Coastal Plain (Lang et al. 2012).

Topographic metrics were calculated using a DEM derived from LiDAR data that were collected when very little flooding was present within study area wetlands. It is critical to collect LiDAR data for topographic analysis when flooding is not present since flooding often leads to inaccurate and/or undependable elevation measurements. For this reason data were collected in December 2007 during a relatively dry period with very little wetland inundation on the landscape. The resultant LiDAR data were used to generate a 9.84 ft (3 m) gridded DEM which was subsequently filtered before applying multiple algorithms to produce five different topographic metrics (Lang et al. 2012). Topographic wetness indices were produced using the basic equation detailed above and the D8, D∞,

Figure 2: Topographic index products including the enhanced topographic wetness index (A), local terrain normalized relief (B), and the relief enhance topographic wetness index (C), LiDAR intensity during an average (D) and dry spring (E), and false color near-infrared aerial photograph (F; collected coincident to D) of a forested wetland complex. All images have been overlaid with a wetland map produced for the Maryland Department of Natural Resources. On the topographic index products, wetter areas are blue (more likely to be wetlands) while drier areas are red (less likely to be wetlands). Inundated areas are black on the LiDAR intensity images. Adapted from Lang et al. 2012.



and FD8 flow-routing algorithms. A local terrain normalized relief (LTNR) map was created by subtracting a surface representing maximum elevation per 0.049 acre (200 m^2) from the original filtered 9.84 ft (3 m) DEM. An enhanced topographic wetness index (ETWI) was created by increasing FD8 based topographic wetness index values within depressions (i.e., pits or sinks). A Relief Enhanced TWI (RETWI) was created by adding the ETWI and LTNR metrics together after normalizing the metrics. The topographic metric-based wetland maps were compared with LiDAR intensity derived maps of inundation created to represent maximum yearly hydrologic expression during average weather (March 2007) and drought conditions (March 2009), and a wetland map produced by the Maryland Department of Natural Resources (MD DNR) (fig. 2)

The ability of the FD8 TWI to map inundation status, and therefore wetland status (see above), was superior to the D∞ and especially the D8 TWIs (Lang et al. 2012). The utility of the FD8 TWI was improved by increasing values within areas without a surface water outlet to create the ETWI. The outlet enhanced FD8 TWI (ETWI) performed well for wetland mapping but provided little information on hydroperiod. Local relief (LTNR) provided information on hydroperiod but was less capable of wetland mapping. Combining local relief and ETWI produced a map that was well suited for mapping wetland extent and hydroperiod. Wetlands mapped using aerial photographs and LiDAR-derived DEMs contained a similar amount of inundated area, but the LiDAR-derived maps contained fewer errors of omission.

Our results support the use of more distributed (FD8) flow routing algorithms over algorithms that encourage greater flow convergence (e.g., D8 and D∞) for the mapping of palustrine wetlands (Lang et al. 2012). This may be especially true in areas of low topographic relief. It is hypothesized that the ETWI map more completely represented the presence of surface water outlets from a given area to complement the input of surface water (i.e., specific catchment area). The ability of the local relief index (LTNR) to indicate temporal trends in flooding could support the use of this index to map hydroperiod and indicate critical zones associated with climate change. We hypothesize that LTNR and RETWI are dependent on two different physical drivers, surface expression of groundwater and lateral inflows and outflows, respectively (Lang et al. 2012). The metrics discussed above provide some degree of flexibility to best represent wetland distribution and boundaries within different study sites. Furthermore, topographic metrics illustrate gradual changes through space, which more accurately depict natural ecologic gradients, instead of the abrupt boundaries present on classified maps.

This study demonstrated that the predictive power and efficiency of wetland mapping efforts could be improved through the incorporation of LiDAR-derived DEMs (Lang et al. 2012). The use of LiDAR data will be especially vital in areas with low topographic variation or when applied to mapping wetlands that have previously been difficult to detect, such as forested wetlands. Optical (e.g., aerial photography) and LiDAR data are distinct remotely sensed datasets which offer unique benefits and limitations. The synergistic combination of these datasets has the potential to significantly improve not only the mapping of forested wetlands but also the mapping of historic wetlands (e.g., prior-converted croplands) within agricultural watersheds. These historic wetlands are critical agricultural management zones that can exert substantial control on crop productivity via nutrient processing (i.e., N and P) and water availability, especially during years of drought or flood.

Current and Future Availability of LiDAR Data and Specifications

Availability of LiDAR data has increased rapidly over the past 2 decades, but these data are not currently available for the entire United States. Although airborne LiDAR data are currently available for only about one-third of the conterminous United States, the spatial distribution of these data are advantageous for wetland mapping (Snyder and Lang 2012). LiDAR data happen to be available where wetlands are most common. A concerted effort is being made by NRCS and other Federal agencies to hasten the collection of high quality LiDAR data throughout the entire United States. The U.S. Geological Survey (USGS) recently conducted the National Enhanced Elevation Survey (NEEA) to assess the needs for, costs of, and best implementation scenarios for the collection of enhanced elevation data (Snyder and Lang 2012). As a result of the NEEA, the USGS has endorsed an implementation scenario focused on the collection of interferometric SAR data in Alaska and LiDAR data with a horizontal point spacing of 2.30 ft (0.70 m) and a vertical accuracy of 3.64 in (9.25 cm) throughout the rest of the United States (Snyder and Lang 2012). The NEEA concluded that there were no technical barriers or capacity issues that would prevent a national program, nor technical reasons to delay national program implementation (Snyder and Lang 2012). NRCS is currently working with USGS to develop a funding strategy and governance model to best assure the collection of the endorsed dataset.

The rapid evolution of LiDAR technology and growth in data availability and use led to a lag in developing LiDAR guidelines and, to some degree, applications. However, LiDAR guidelines were recently developed and are currently available to guide LiDAR collection and processing (e.g., http://pubs.usgs.gov/tm/11b4/). Continued application development is needed to fully realize the potential of LiDAR data for wetland mapping and assessment. This effort includes the development of optimal data collection specifications for different applications. LiDAR data should be collected to different specifications based on their intended application. For example, vegetation cover is known to reduce the spatial resolution and accuracy of bare earth DEMs. For that reason data are best collected for this purpose during the leaf-off period. Resolution can be further improved by collecting data at higher point densities. Fundamental research studies, such as those described in this document, have demonstrated the strong potential of LiDAR to support wetland assessment and management. Further advancements in LiDAR applications would greatly benefit from investigation of the suitability of developed techniques within an operational mapping and assessment framework. Perhaps most critical for wetland applications is consideration of ecosystem hydrologic state relative to the goal of the data collection. For example, obtaining detailed maps of actual and potential inundation extent from LiDAR requires contrasting hydrologic states and therefore careful planning of data acquisition within the hydrologic cycle.

Potential of LiDAR for Future Wetland Conservation and Management Efforts

The wetland science and management community has rapidly endorsed the use of LiDAR data for improved wetland mapping and characterization, which is likely attributable both to the considerable benefit of LiDAR and the poor suitability of older datasets for this application. Indeed, wetland-related applications were among the most commonly cited applications in the NEEA report (Snyder and Lang 2012). The future holds promise for increased data availability and consistency, more robust and accessible software and hardware processing capabilities, further development of applications, and increased integration of LiDAR data into the operational geospatial data -processing chain. This increased capability is well timed since it will become even more vital to map and monitor not only current wetland extent and function but also changes with predicted climate and land use change. LiDAR intensity and elevation data provide synergistic information that can be used for this purpose. LiDAR elevation data can be used to map the potential, static distribution of current and historic wetlands and key wetland functional drivers based on physical controls on water distribution. LiDAR intensity data can be used to map actual, dynamic variations in wetland extent and key functional drivers. The current use of LiDAR data, including the applications described in this CEAP Science Note, support the improved management of wetlands and serve as a foundation upon which to develop even more advanced LiDAR applications that would benefit from improvements in LiDAR technology and availability.

The Conservation Effects Assessment Project: Translating Science into Practice

The Conservation Effects Assessment Project (CEAP) is a multi-agency effort to build the science base for conservation. Project findings will help to guide USDA conservation policy and program development and help farmers and ranchers make informed conservation choices.

One of CEAP's objectives is to quantify the environmental benefits of conservation practices for reporting at the national and regional levels. Because wetlands are affected by conservation actions taken on a variety of landscapes, the wetlands national assessment complements the national assessments for cropland, wildlife, and grazing lands. The wetlands national assessment works through numerous partnerships to support relevant assessments and focuses on regional scientific priorities.

This assessment was conducted and this paper written by Dr. Megan Lang, University of Maryland, Department of Geographical Sciences, College Park, MD, and Dr. Greg McCarty, USDA Agricultural Research Service Hydrology and Remote Sensing Lab, Beltsville, MD

For more information: http://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/ceap, or contact Bill Effland at william.effland@wdc.usda.gov.

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