# On the potential for high-resolution lidar to improve rainfall interception estimates in forest ecosystems

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**Closing the gaps in the water budget of forested ecosystems is a first-order challenge, with immediate implications for regional water supply, ecosystem function, and landscape biogeochemistry. Rainfall interception by vegetated canopies can be as great as 50% of total rainfall. There is considerable uncertainty in predicting this ecosystem property, which makes it one of the primary constraints in spatial water budgeting. Interception is largely controlled by vertical structure and canopy gaps on a relatively small scale. Emerging remote sensing technologies, such as lidar (light detection and ranging), now offer an unprecedented opportunity to quantify canopy architecture in three dimensions across the landscape. Use of such high-resolution spatial data, along with improved rainfall interception models, will aid in ecosystem process studies and the development of tools and incentives that could influence land-use policy and decision making in the future.**

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There is a crucial need to understand ecological water balances, both in the present and in the future. This balance is currently shifting, as economies rapidly develop and urbanization accelerates (Hubacek and Sun 2005). In the future, global climate change and the resulting uncertainties will only add to the urgency of finding accurate and reliable prediction tools that can be used to understand regional water supply, ecosystem function, and landscape biogeochemistry. For nearly a century, researchers have developed hydrologic models to this end, but their effectiveness has been hampered by a shortage of detailed data (Singh and Woolhiser 2002).

Canopy interception of rainfall is a key component in the hydrologic cycle (Figure 1). In closed-canopy ecosystems, the canopy can intercept as much as 10–50% of incoming total precipitation, depending on a variety of factors. This intercepted rainfall may be evaporated to the atmosphere (interception loss), absorbed by the canopy (storage), channeled downward along branches and stems (stemflow), or dripped to the ground (throughfall). Recent investigations have indicated that canopy structure, in combination with rainfall regime (ie short, intense versus long, sustained rainfall events), influences rainfall interception and evaporation to a greater extent than previously recognized (Liu 2001). Canopy structure is extremely difficult to quantify due to its high three-dimensional (3-D) spatial variability over relatively short distances (Pypker *et al.* 2005). In extreme cases, researchers have resorted to using construction cranes to obtain detailed canopy structural measurements (Nadkarni and Sumera 2004). Emerging remote sensing technologies such as lidar (light detection and ranging) offer the ability to collect 3-D canopy structural information at a resolution that has not previously been attainable (Lefsky *et al.* 1999).

A better understanding of how rainfall is intercepted by the canopy of trees will broadly impact ongoing ecological research. The interacting processes that influence the amount and distribution of rainfall interception across a landscape remain somewhat poorly understood, and are difficult to model. For example, rainfall interception by forested canopies depends on individual rainstorm intensity, duration (Keim *et al.* 2004), and nominal droplet size (Murakami 2006). Thus, interception varies dramatically with the characteristics of rainfall events and the heterogeneity of gaps in the canopy (Liu 2001). Interception loss via evaporation from branch and leaf surfaces is depen-

## In a nutshell:

- Quantifying the water balance of forested ecosystems has implications for regional water supply, ecosystem function, and landscape biogeochemistry
- Interception of rainfall is a key component of the water balance equation and is largely controlled by canopy structure
- Emerging remote sensing technologies, such as lidar, offer an opportunity to quantify three-dimensional canopy architecture
- Detailed prediction of rainfall interception and an understanding of ecosystem-process controls could influence land-use and policy decisions

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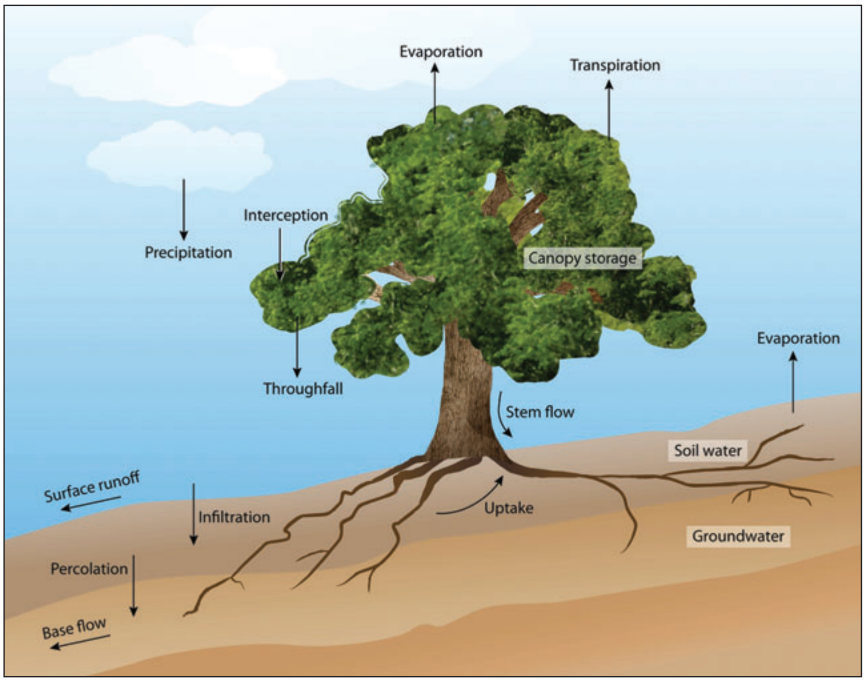


***Figure 1.*** *Water balance of a forested ecosystem. Precipitation that is intercepted by the canopy may be evaporated to the atmosphere (interception loss), absorbed by the canopy (storage), channeled downward along branches and stems (stemflow), or dripped to the ground (throughfall).*

dent on the wetness of the canopy at the time of the rainfall event, aerodynamic roughness, and concurrent meteorological conditions (latent and sensible heat; Rutter *et al.* 1971). Ultimately, this controls the amount of water that reaches the ground through the canopy.

Incoming rainfall is intercepted by non-uniformly distributed leaves and branches of trees of differing sizes, species, and arrangement in forested ecosystems. The result is that, at the forest-stand level, spatially uniform incoming rainfall is partitioned into spatially heterogeneous components of interception (evaporation plus canopy storage), throughfall, and stemflow, leading to an uneven spatial distribution of precipitation at the ground surface (Fleischbein *et al.* 2005). This has important ecological implications for the distribution of soil moisture, organic matter content, and soil nutrient cycling (Qualls and Haines 1991). Rainfall interception also varies over time, due to short-term fluctuations in rainfall intensity and longer-term seasonal variation in canopy cover, such as with deciduous tree species (Bryant *et al.* 2005). Gaps in the canopy allow gross precipitation to pass directly to the ground as a proportion of total throughfall. Traditional methods for quantifying this fraction are challenging and widely varying estimates of throughfall can result, especially for low-intensity rainfall events (Carlyle-Moses *et al.* 2004).

Forested canopies have the ability to store the water they intercept in fine branches, bark, dead wood (Crockford and Richardson 2000), and, to a lesser extent, in leaves (Kerstiens 1996). This water store can make up a substantial proportion of the hydrological budget of cloud forests in certain ecosystems (Holder 2004). Epiphytes in the canopy and on stems also influence the interception and storage of water, and this varies according to the individual species, abundance, position, and water-holding capacity (Pypker *et al.* 2004). Another source of water input is fog or occult precipitation, whereby suspended water droplets are intercepted by fine structures in the canopy (Holder 2004). The storage of this moisture can maintain elevated canopy wetness, which in turn greatly modifies canopy interception in subsequent rainfall events.

## Modeling canopy interception

Horton (1919) was the first to attempt to quantify interception of rainfall of various canopy types through the development of empirical formulas for estimating losses during a storm. Since that time, many interception models have been created, which can be grouped into three general categories: (1) empirical (Merriam 1960; Czarnowski and Olszewski 1986), (2) stochastic (Calder 1968), and (3) physical and related (Rutter *et al.* 1971; Gash 1979). Canopy structural properties are a driving factor in many of these models. Newer models have resulted in great improvements in the estimation of rainfall interception and throughfall via recreation of the 3-D canopy structure (Houldcroft *et al.* 2005). Further improvements can be seen if fine-scale parameterization of the canopy in time and space is achieved. Canopy surface area and leaf area index (LAI) have a major impact on interception and are most often utilized as inputs in these improved models (Zeng *et al.* 1996). However, most of the data used to construct these models is derived from forests with varying canopy structural properties, but similar LAI (Pypker *et al.* 2005). Models with the highest resolution in their ability to predict rainfall interception incorporate 3-D stochastic equations with input parameters at the scales of a single leaf or branch segment, up to the individual-tree level (Xiao 2000). While these models can provide very accurate estimates of rainfall interception, the question remains: how can detailed estimates of 3-D canopy structure, which are required model inputs, be obtained over large areas with minimal effort?

The science of hydrology in general, and predictions of rainfall interception in particular, have historically been data-limited. For example, estimates of canopy structure were often derived from light-interception relationships, such as the Beer-Lambert Law (or Beer's Law), which work on the principle of light transmittance (Fleischbein *et al.* 2005). However, there are serious drawbacks to this

 

**Table 1. Examples detailing the potential for improvement in rainfall interception estimates via lidar measurements**

| *Rainfall partitioning coefficient** | *Related canopy propery* | *Model estimate* | | *Lidar measurement* | |
|---|---|---|---|---|---|
| | | *Source* | *Precision* | *Source* | *Precision* |
| Throughfall | Canopy gap fraction | Rutter 1971; Gash 1979; Liu 1997 | 5% | Means *et al.* 1999 | 1% |
| | Tree density | Teklehaimanot and Jarvis 1991 | Single tree | Hall *et al.* 2005 | Single tree |
| | Leaf area index | Fleischbein *et al.* 2005; Pypker *et al.* 2005 | 0.1 $m^2 m^{-2}$ | Houldcroft *et al.* 2005 | 0.1 $m^2 m^{-2}$ |
| | Tree height | Dietz *et al.* 2006 | 0.1 m | Drake *et al.* 2002; Hall *et al.* 2005 | 0.01 m |
| | Lower crown limit | Dietz *et al.* 2006 | 0.1 m | Hall *et al.* 2005 | 0.01 m |
| | Basal area | Dietz *et al.* 2006 | 0.01 $m^2 ha^{-1}$ | Drake *et al.* 2002; Hall *et al.* 2005 | 0.01 $m^2 ha^{-1}$ |
| Storage | Canopy biomass | Calder and Wright 1986; Hutchings *et al.* 1988 | 0.1 kg $m^{-2}$ | Hall *et al.* 2005 | 0.01 kg $m^{-2}$ |
| | Canopy area index | Liu 1998 | 0.01 $m^2 m^{-2}$ | Parker *et al.* 2004 | 0.01 $m^2 m^{-2}$ |
| | Leaf area index | Liu 1998 | 1 $m^2 m^{-2}$ | Houldcroft *et al.* 2005 | 0.1 $m^2 m^{-2}$ |
| | Stem diameter | Liu 1998 | 1 cm | Henning and Radtke 2006 | 0.1 cm |
| | Branch diameter | Liu 1998 | 1 cm | Lucas *et al.* 2006 | 1 cm |
| Stemflow | Branch inclination angle | Levia and Herwitz 2002 | 20 degree increments | Lucas *et al.* 2006 | 0.01 degree increments |

**Notes**: Table outlines specific canopy properties in common between those estimated in models and those measured with lidar; * = as per existing rainfall models (Rutter 1971; Gash 1979; Liu 1997); precision as determined from published work

method, especially where the foliage and branches in the canopy are highly aggregated, as is the case with pine trees (Gholz *et al.* 1991). The solution to this problem may come in the form of remote sensing tools that can provide detailed information at the landscape level (Li 2003). Lidar is a new technology, capable of yielding large quantities of 3-D structural canopy data, which can be used to improve the model parameters that partition gross rainfall input into throughfall, stemflow, and canopy storage components. While we are unaware of any specific cases in which lidar data have been used to provide rainfall interception estimates, we do make a case for this link with specific examples from the hydrology and lidar fields (Table 1). In general, the lidar-derived estimates of canopy variables are on the order of 10 times more precise than those used in models to date.

## ■ Lidar: an emerging technology

Airborne lidar systems designed to collect range measurements of the bare-ground surface were originally developed as a military application for improving digital terrain-elevation mapping. In the past 15 years, commercially available, discrete (eg first and last return as opposed to the entire waveform), airborne lidar systems have been developed. These systems consist of four major hardware components: (1) a laser emitter–receiver scanning unit, (2) differential global positioning systems (GPS; aircraft and ground units), (3) a highly sensitive inertial measurement unit (IMU), and (4) a computer for system control and data storage (Figure 2). While much of the early research in lidar was focused on removing extraneous information about the vegetated layer, researchers are now capturing a wealth of information that can be used in process-based ecological studies across large scales.

One example involves studies of the canopy architecture in forested ecosystems. Modern lidar systems can provide detailed information about the spatial distribution of gaps in the canopy, the distribution of trees on the landscape, canopy depth, canopy bulk density, canopy surface area, and leaf area index (Means *et al.* 1999). Traditionally, various two-dimensional (2-D) image-based remote-sensing modalities, such as synthetic aperture radar (SAR) and multispectral or hyperspectral imagery, have been used to estimate forest structural parameters (Butson and King 2006); however, these image-based methods often require assumptions of uniform forest structure in the horizontal dimensions over various distance scales. These methods of utilizing 2-D data are suboptimal,

 

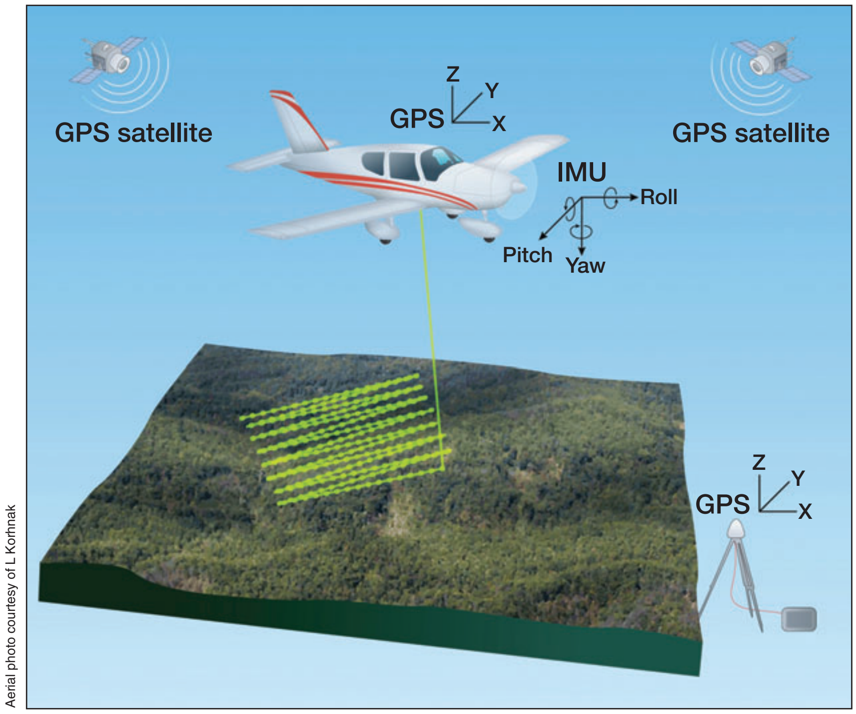


***Figure 2.*** *Schematic diagram showing lidar data collection over a forested watershed. Lidar systems are generally comprised of four major hardware components: (1) a laser emitter–receiver scanning unit, (2) differential global positioning systems (GPS; aircraft and ground units), (3) a highly sensitive inertial measurement unit (IMU), and (4) a computer for system control and data storage.*

since it is well known that forest canopies exhibit significant structural variations in all three spatial dimensions.

Image-based methods have also been used to obtain limited 3-D information from forest canopies (eg interferometric synthetic aperture radar or InSAR; Slatton *et al.* 2001) and multi-frequency SAR (Mougin *et al.* 1999). These methods exploit the varying wavelengths of microwave energy penetrating foliage. However, the horizontal and vertical resolutions are generally insufficient to adequately capture canopy variation at the tree or branch level. Airborne lidar systems, on the other hand, can provide both high spatial resolution and deep-canopy penetration by using high laser-pulse rates and narrow beam divergence. Thus, there is high potential for lidar measurements to be useful in the estimation of forest canopy parameters that modulate the spatial distribution of rainfall interception.

## Lidar systems

There are two major classes of airborne laser-ranging technologies currently in use: (1) large-footprint, full-waveform systems and (2) small-footprint, discrete-return systems. Large-footprint lidar systems, such as the NASA Laser Vegetation Imaging Sensor (LVIS; Drake *et al.* 2002) and Scanning Lidar Imager of Canopies by Echo Recovery (SLICER; Lefsky *et al.* 2002), generally have footprint diameters of tens of meters on the ground. The return signal is finely sampled over a long distance between the sensor and the object reflecting the digitized laser waveform. Because the large footprint spreads the transmitted photons over a wide area, many photons penetrate deep into the canopy, providing a densely sampled, vertical profile at a coarse resolution. This configuration makes large-footprint systems well suited for estimating the vertical distribution of certain forest biophysical parameters over a wide area.

However, large-footprint systems are incapable of sensing horizontal variations in canopy structure at the scale of one meter or less. This limitation is due to the fact that the received waveform is a representation of the integrated response for the entire area illuminated by the footprint. Since an infinite number of structural configurations can result in the same waveform shape, non-unique mappings to forest structure can result. For example, consider a patch of forest illuminated by a circular footprint 10 m in diameter. The return waveform will remain constant under rotation of the imaged footprint about the laser bore sight. Also, full-waveform lidar sensors primarily remain research tools, due to the excessive data volumes and per-unit-area acquisition costs. As an alternative, NASA has developed an experimental system, Experimental Advanced Airborne Research Lidar (EAARL), which combines waveform digitization with small footprints (Brock *et al.* 2004). However, the laser pulse rate is comparatively low, which reduces terrain sampling rates, thereby limiting the area that can be covered using this system.

Commercially manufactured, discrete-return, small-footprint lidar systems are by far the most widely available lidar technology for the earth science and forest management communities. Small-footprint lidar can provide very high resolution 3-D positions of millions of laser pulses that intercept the ground or landcover (Popescu *et al.* 2004). Area-point densities on the order of 10 per $m^2$ are readily achieved by using overlapping flight lines or narrow scan patterns. When differential GPS processing, modern IMUs, and sensor calibration are employed, absolute (geo-referenced) position accuracies on the lidar points of 30 cm x 30 cm x 10 cm in the XYZ plane are typical.

## Parameter estimation from lidar

Given a discrete-return, small-footprint lidar dataset, many parameters relevant to forest structure and, consequently, rainfall interception modeling can be estimated. Analysis generally begins by estimating the topographic elevations of the underlying forest floor. Typically, filtering algorithms are applied in order to estimate the bare-surface elevations by "filtering out" the vegetation contribution to the signal. A probabilistic approach can be used, which involves a hierarchical data-point segmentation procedure (Kampa and Slatton 2004).

Once the lidar points are segmented into ground and non-ground classes, the non-ground points can be used to study canopy structure (Figure 3). In some cases, the non-ground points are simply gridded to form a 2-D image that is related to parameters such as crown area. These non-ground lidar points can be used to numerically estimate foliage density in three dimensions at a high spatial resolution. Light interception by forest canopies has also been predicted by quantifying the distribution of lidar return points between any location on the forest floor and the sun (Slatton *et al.* 2005; Figure 4). In all these applications, however, care must be taken if the lidar sensor provides only first and last returns. Such two-return lidar sensors generally sample the upper canopy and the ground sufficiently, but may under-sample the lower canopy and understory layers.

Lidar systems can also be deployed in a ground-based mode, whereby lateral scans of tree stems and understory vegetation are obtained (Figure 5). While ground-based lidar systems have a range of several hundred meters if not occluded, scans in the forest generally acquire useful returns from the first 50 to 100 meters. Within this range, however, these sensors can image the geometry of stems and branches in great detail (Lucas *et al.* 2006) and with greater precision than used in past modeling efforts. Such data have the potential to be very useful for estimating the parameter coefficients for stemflow, canopy storage, and throughfall in rainfall interception models.

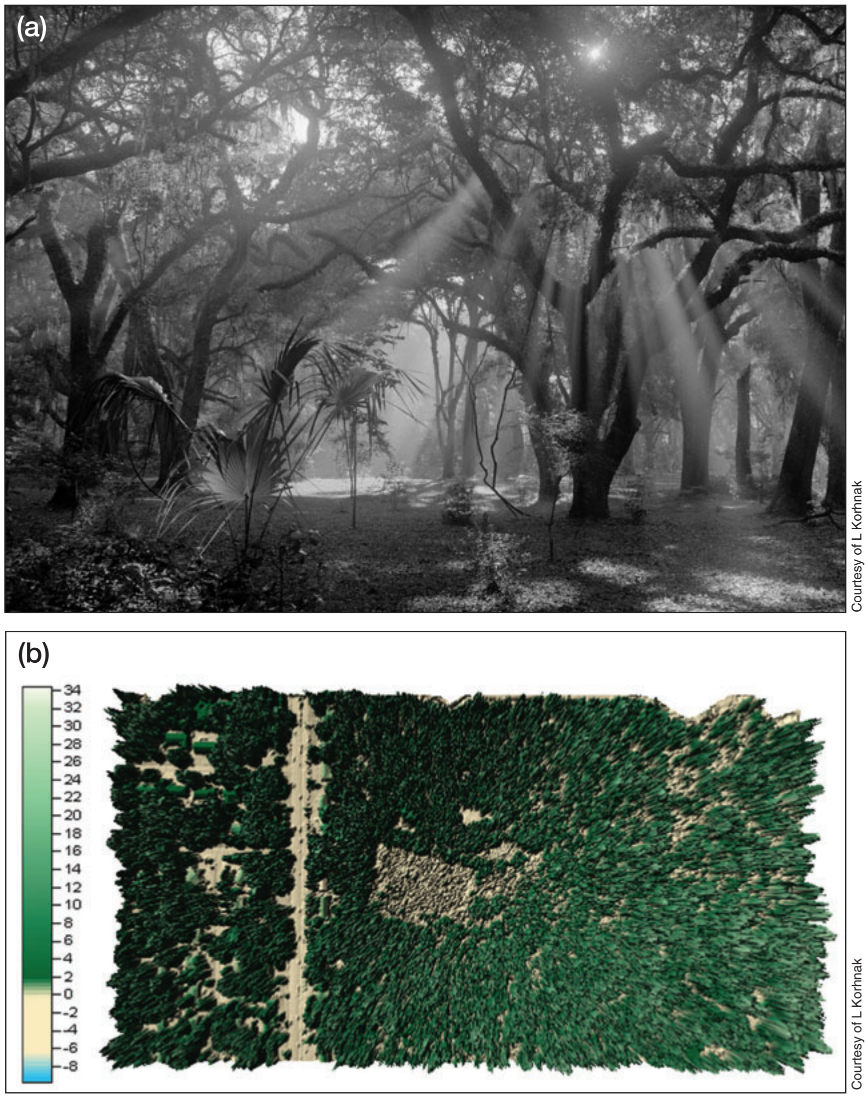


***Figure 3.*** *(a) Black-and-white photograph of a complex forested canopy in north-central FL, demonstrating the canopy structural properties that influence rainfall interception. (b) Lidar first-return point surface over a forested watershed in Gainesville, FL. The image is 700 m x 400 m at a data density of approximately one point per* $m^2$*. This image was created in Surfer software by kriging (interpolating) the first return point to obtain a "top surface". The colored legend represents the relative height in meters.*

## Data centers

Large amounts of data are being collected on canopy structure and water balance estimates in US ecosystems and around the globe. Currently, this information is not readily accessible to researchers who could make use of it. This problem is shared by many ecological research programs and has recently spurred the development of several data-oriented research centers (Table 2). The National Science Foundation (NSF) has established the National Ecological Observatory Network (NEON) in order to develop instrumentation, acquire regional climate and hydrological data, and disseminate

**Table 2. Networks with the potential to provide data to improve rainfall interception estimates**

| *Group name* | *Acronym* | *Website address* |
|---|---|---|
| National Ecological Observatory Network | NEON | www.neoninc.org |
| Center for Embedded Network Sensing | CENS | www.cens.ucla.edu |
| Long Term Ecological Research network | LTER | www.lternet.edu |
| National Center for Airborne Laser Mapping | NCALM | www.ncalm.ufl.edu |

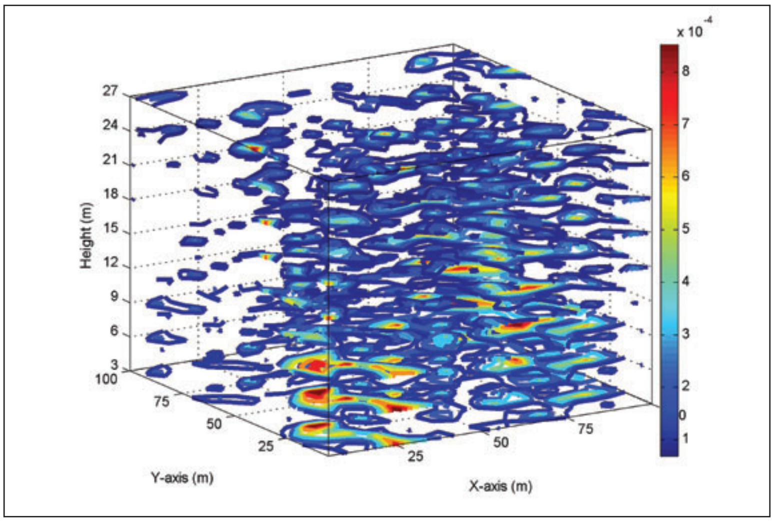


***Figure 4.*** *A high-resolution 3-D map of the relative probability density of light interception derived from the lidar point cloud in a 100 m x 100 m section of the forest, as presented in Figure 3. The legend represents the fraction of the total number of laser returns occurring in a given volume. Red colors indicate a higher probability of light interception, while blue colors indicate a lower probability. The probability of light interception correlates with biophysical parameters, such as leaf area or canopy biomass.*

that data to researchers interested in understanding and forecasting ecological dynamics at various temporal and spatial scales. Additional ecosystem data on forested systems are available through the LTER (Long Term Ecological Research) network. Complementary to this, NSF has also established the National Center for Airborne Laser Mapping (NCALM) to support the use of airborne laser mapping technology in the scientific community.

Vast amounts of detailed data on gross precipitation, throughfall, evaporation, and stemflow must be collected over fairly wide areas in order to update and validate new and existing interception models. The most logical solution for the collection of this spatially and temporally dense in situ data is to deploy multiple environmental sensors connected through wireless networks (Xiao *et al.* 2000). These data could then be fused with independently collected lidar data that describes the structure of the associated canopy. The Center for Embedded Network Sensing (CENS) offers a solution for the collection of environmental data via wireless networks and is one of six such centers established in 2002 by NSF. The goals of these centers include: (1) embedding numerous distributed devices to monitor and interact with the physical world, (2) networking these devices to coordinate and perform higher level tasks, and (3) tightly coupling these sensors to the physical world.

## Conclusions

Improved estimates of canopy structure will undoubtedly lead to better estimates of rainfall interception across diverse landscapes. Opportunities to improve existing rainfall-interception model parameterization through the use of high-resolution canopy architecture data are close at hand. For example, simply adjusting for changes in leaf area of a deciduous canopy between growing and dormant seasons has improved existing interception models

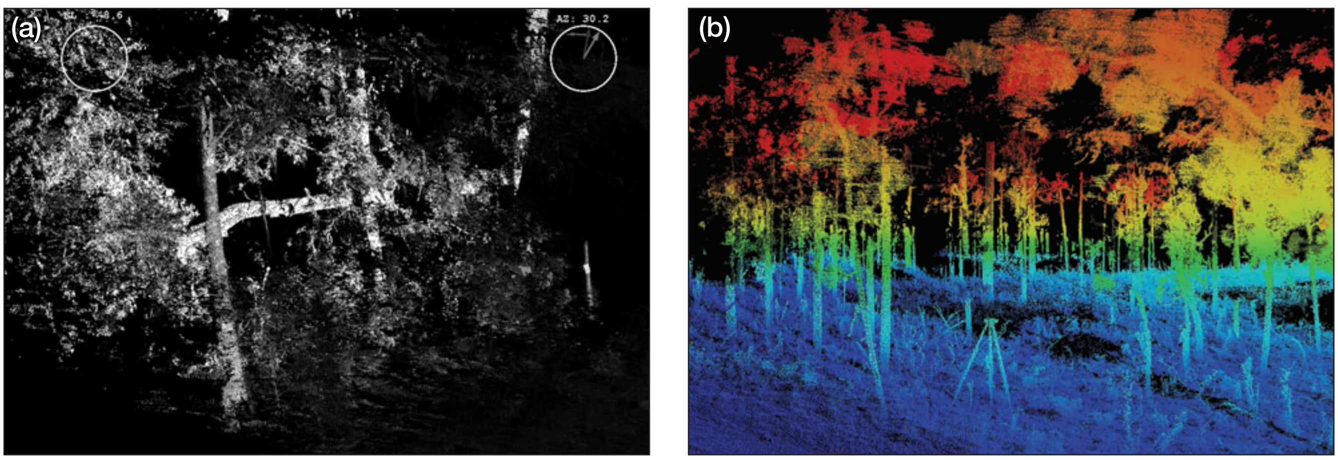


***Figure 5.*** *(a) A ground-based 3-D lidar scan taken in the forest, as shown in Figure 3b. Details such as foliage density, branch structure, stem form, and bark texture could be quantified and used for rainfall interception model parameterization. Data were collected using an Intelligent Laser Ranging and Imaging System (ILRIS) with a maximum field of view of 40° vertical by 40° horizontal. Data resolution was 9 mm, and a total of 1 251 632 laser returns were collected to generate this dataset. The 10-m wide image was created using QT Modeler software. Brightness is proportional to intensity of laser return. Circular symbols refer to the reference ILRIS instrument elevation. EL = meters from the ellipsoidal height and AZ = azimuth in degrees from true north. (b) A 3-D ground-based scan of a longleaf pine sandhill ecosystem at the Ordway-Swisher Biological Station near Melrose, FL (www.ordway.ufl.edu). The 7-m x 5-m image was generated using ILRIS data collected at a 1-cm point spacing and field of view of 40° vertical by 40° horizontal. The colors represent height gradients, with blue corresponding to the ground surface and red corresponding to the upper canopies of the tallest trees.*

 

(Deguchi *et al*. 2006). These models can be further improved if high resolution, 3-D data representing crown structure are used as inputs. Stratifying detailed 3-D canopy data into layers is an obvious approach.

The fusion of remote sensing technologies, such as hyperspectral imagery and lidar, has presented diverse groups of interdisciplinary research teams with the ability to finely tune models of rainfall interception and water yield (Power *et al*. 2005). Along with better estimates of rainfall estimation, improved models can enable hypothesis testing of controls on ecosystem processes, such as variation through time associated with changes in canopy characteristics (Gholz *et al*. 1991), age of forested systems (Pypker *et al*. 2005), or recovery of watersheds from disturbance (Mackay and Band 1997). Detailed lidar-derived interception data can also be fed into existing, spatially explicit hydrologic models to investigate hydrologic changes in response to shifts in land cover, an understudied issue. Equipped with this knowledge, managers and policy makers will have better information and tools to address the impact of land-use changes in the face of a changing climate. This has recently been accomplished in Sacramento, California's urban forest, where researchers used a combination of existing models and detailed remote-sensing data to estimate the influence of rainfall interception on water quality and flood control (Xiao *et al*. 1998). With the emergence of this new technology, there will be numerous opportunities to address current or longstanding ecological and environmental issues.

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