Progressive forest canopy water loss during the 2012–2015 California drought

Gregory P. Asner[1], Philip G. Brodrick, Christopher B. Anderson, Nicholas Vaughn, David E. Knapp, and Roberta E. Martin

Department of Global Ecology, Carnegie Institution for Science, Stanford, CA 94305

Contributed by Gregory P. Asner, November 30, 2015 (sent for review November 10, 2015); reviewed by Craig D. Allen and Robert Green)

The 2012–2015 drought has left California with severely reduced snowpack, soil moisture, ground water, and reservoir stocks, but the impact of this estimated millennial-scale event on forest health is unknown. We used airborne laser-guided spectroscopy and satellite-based models to assess losses in canopy water content of California's forests between 2011 and 2015. Approximately 10.6 million ha of forest containing up to 888 million large trees experienced measurable loss in canopy water content during this drought period. Severe canopy water losses of greater than 30% occurred over 1 million ha, affecting up to 58 million large trees. Our measurements exclude forests affected by fire between 2011 and 2015. If drought conditions continue or reoccur, even with temporary reprieves such as El Niño, we predict substantial future forest change.

canopy water | climate change | drought | forest health | imaging spectroscopy

California has undergone progressive drought since 2012, with the cumulative rainfall deficit in 2015 described as a one in a 1,000-y event (1). As a result, concern has grown over the ecological and societal effects of the drought throughout the environmental conservation, management, and resource policy communities (2). Such concerns are likely to increase as rising temperatures interact with droughts in California and around the world (3–5).

Forests of California are of particular interest because they include the tallest, most massive, and oldest trees on Earth, as well as provide a wide variety of goods and services to the state of California and the world. These services include habitat for numerous plant and animal species, carbon storage for climate change mitigation, water provisioning for a myriad of industries and communities, timber for wood products, and ecotourism (6). Combined with high air temperatures and insect infestations, the 2012–2015 drought has generated a large pulse of tree mortality in California (7). This event may have cascading effects on forest fire susceptibility and severity, animal habitat and biological diversity, water resources, and carbon sequestration. However, tree mortality mapping provides a limited understanding of forest vulnerability and adaptation, because the observations do not directly resolve forest physiological responses to ongoing changes in climate. To improve predictions of how forests will change in the future, spatially and temporally continuous measurements of canopy functional responses to climate change are needed.

Monitoring forest canopy physiology in the context of drought and other climate perturbations has proven challenging, because the onset and progression of canopy stress is not easily revealed in traditional satellite observations (8). Newer technologies, such as high-fidelity imaging spectroscopy (HiFIS), may help to break this barrier (9, 10). HiFIS measures the spectral radiance reflected from the land surface in narrow, overlapping, and contiguous spectral channels (11). After compensation for illumination and atmospheric effects, HiFIS-measured spectral reflectance yields quantitative measurements of the mass-concentration of biologically important molecules and elements (12–15), some of which are diagnostic and predictive of vegetation responses to climate change.

One of the most operational HiFIS measurements is canopy water content (CWC), which is the total amount of liquid water in the foliage of a canopy. CWC is an indicator of tree physiological status because it underpins important plant functions, including light interception and growth (16–18). It is broadly correlated with leaf water potential during times of water stress (19–21), and thus has served as an indicator of progressive drought effects on forest canopies (8). CWC is also a useful predictor for vegetation flammability (22). CWC can be estimated from HiFIS in units of water volume (e.g., liters) in the canopy on a per area (e.g., square meter) basis, derived from the depth and shape of 118 spectral absorption features centered at 980 nm and 1,160 nm (23, 24). By combining HiFIS measurements with 3D forest imaging via light detection and ranging (LiDAR) scanning, it is possible to exclude nonforest canopies, such as grasses and short shrubs, as well as bare ground, rock cover, and infrastructure, from the intended measurement (25). This data-fusion technique, called laser-guided HiFIS, allows for the measurement and projection of forest CWC in three dimensions.

HiFIS and LiDAR technologies are not currently available from satellites. The Carnegie Airborne Observatory (CAO) is one of the few systems that can make laser-guided HiFIS measurements on an operational basis (26). Nonetheless, the time needed to cover a large area, such as the ~13.4 million ha of forest in California, requires additional techniques that combine aircraft measurements with an integrated suite of statewide geospatial data (27, 28). We combined airborne laser-guided HiFIS, multivariate satellite and environmental data, and geostatistical modeling to develop high-resolution forest CWC maps of California (*SI Appendix*, Figs. S1–S4 and Table S1).

The airborne and satellite measurements were collected in August 2015, allowing for the derivation of geostatistically robust

Significance

The state of California has a globally important economy and a population exceeding 38 million. The state relies on its forested watersheds to support numerous services, such as water provisioning, carbon storage, timber products, ecotourism, and recreation. However, secular changes in air temperature, combined with periodic and prolonged drought, pose a compounding challenge to forest health. Here we use new remote-sensing and modeling techniques to assess changes in the canopy water content of California's forests from 2011 to 2015. Our resulting maps of progressive canopy water stress identify at-risk forest landscapes and watersheds at fine resolution, and offer geographically explicit information to support innovative forest management and policies in preparation for climate change.

Author contributions: G.P.A. designed research; G.P.A., P.G.B., C.B.A., N.V., D.E.K., and R.E.M. performed research; G.P.A., P.G.B., C.B.A., N.V., D.E.K., and R.E.M. analyzed data; and G.P.A., P.G.B., and R.E.M. wrote the paper.

Reviewers: C.D.A., US Geological Survey; and R.G., Jet Propulsion Laboratory.

The authors declare no conflict of interest.

Freely available online through the PNAS open access option.

[1]To whom correspondence should be addressed. Email: gpa@carnegiescience.edu.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1523397113/-/DCSupplemental.

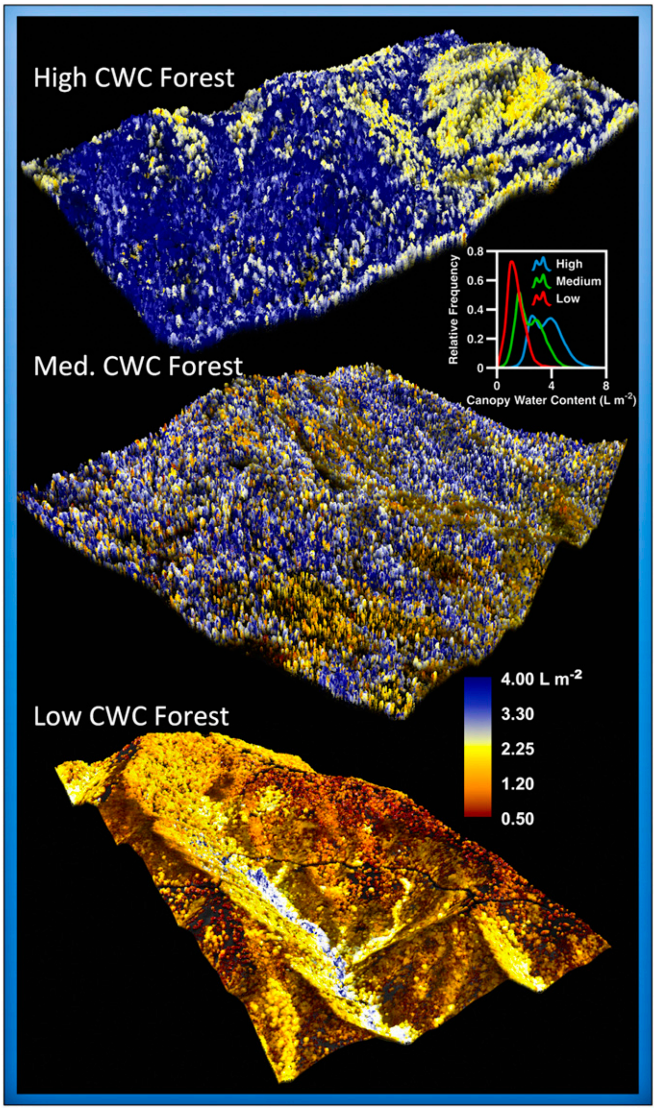

Fig. 1. Example CAO images of forest 3D canopy water content (CWC) highlighting landscapes of about 1,000 ha each, with high, medium, and low CWC. (*Inset*) Graph shows the frequency distribution of CWC in liters of water per square meter (L/m^2). These landscape examples were taken from Muir Woods National Monument (high CWC), Sequoia-Kings Canyon National Park (medium CWC), and Los Padres National Forest (low CWC). Field and airborne observations, as well as US Forest Service studies (7), indicate massive mortality in the low CWC landscape shown.

relationships between HiFIS and satellite data using a deep learning model (*SI Appendix*). These relationships were used to scale up the 2015 HiFIS measurements to the entire forested region of California. In addition, statewide multivariate satellite data were compiled for 2011, 2013, and 2014, and used to retrospectively estimate forest CWC and change from 2011 to 2015 using our modeling technique. The goal was to quantify CWC changes over 4 years as a means to understand forest canopy physiological responses to progressive drought.

Results and Discussion

Forest Canopy Water Content in 2015. Twelve days of flight operations yielded 1.8 million ha of direct airborne CWC estimates at 2-m spatial resolution. Three example landscapes totaling ~3,000 ha are shown in Fig. 1. As depicted in these images, CWC in each landscape strongly varied based on tree species and condition, local topography, and other factors. Across California, we observed enormous CWC variability in the aircraft imagery, with patterns linked to forest type and geographic location throughout the state. Some landscapes were comprised of individual trees with CWC that was greatly suppressed relative to neighboring vegetation. Other landscapes showed widespread suppression of CWC, with spatial patterns following the terrain. These results indicated that the upscaling and modeling of the CWC measurements to statewide maps needed to be accomplished at relatively fine spatial resolution. We selected 30-m × 30-m resolution (0.09 ha) as the resolution for modeling all forests of California (*SI Appendix*).

Ten percent of the original aircraft CWC data were left out of the scaling step to validate the statewide 2015 model. These validation data were selected randomly from aircraft coverage acquired throughout the state, and were comprised of 1.2 million measurements. Regression analyses showed an R^2 of 0.82 and root mean squared error of 0.45 L/m^2 of forest canopy (*SI Appendix*, Fig. S5). Mean absolute deviation was 0.33 L/m^2. These results indicated that the statewide model captures the spatial and ecological patterns of CWC measured using airborne laser-guided HiFIS.

We assessed the importance of environmental factors mediating the patterns of forest CWC as measured by the aircraft sensors (*SI Appendix*). Geographic location and elevation accounted for a large proportion of the measured variation in CWC (*SI Appendix*, Fig. S6). Beyond these factors, a suite of satellite vegetation metrics was important in modeling forest CWC. These metrics included the fractional cover of green leaf photosynthetic vegetation, bare ground exposure, and shortwave-infrared reflectance, the latter being sensitive to canopy water content (29, 30). This suite of satellite-based vegetation measurements were critically important for scaling up the direct CWC observations from airborne laser-guided HiFIS, and for developing retrospective models of change in CWC.

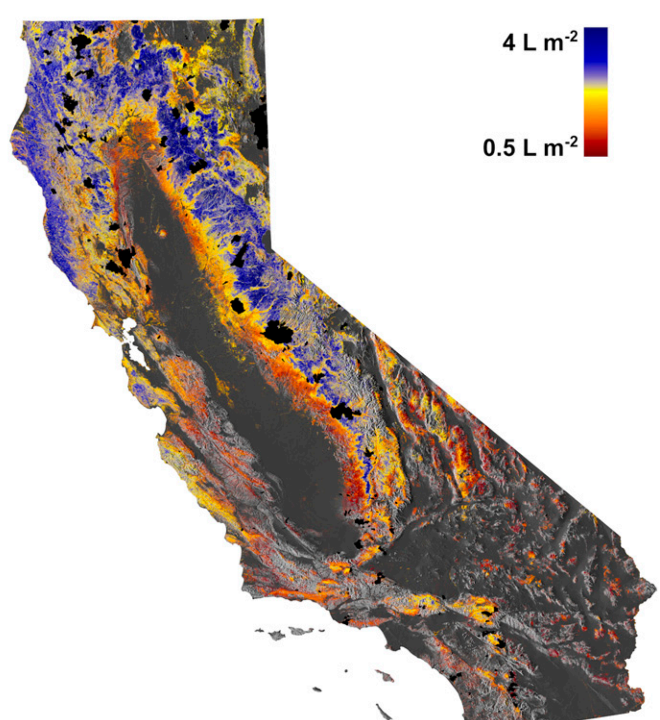

Fig. 2. Forest canopy water content (CWC) reported in liters per square meter for the state of California as of August 2015. Black areas indicate fire extents reported between 2011 and 2015 by the US Forest Service (31).

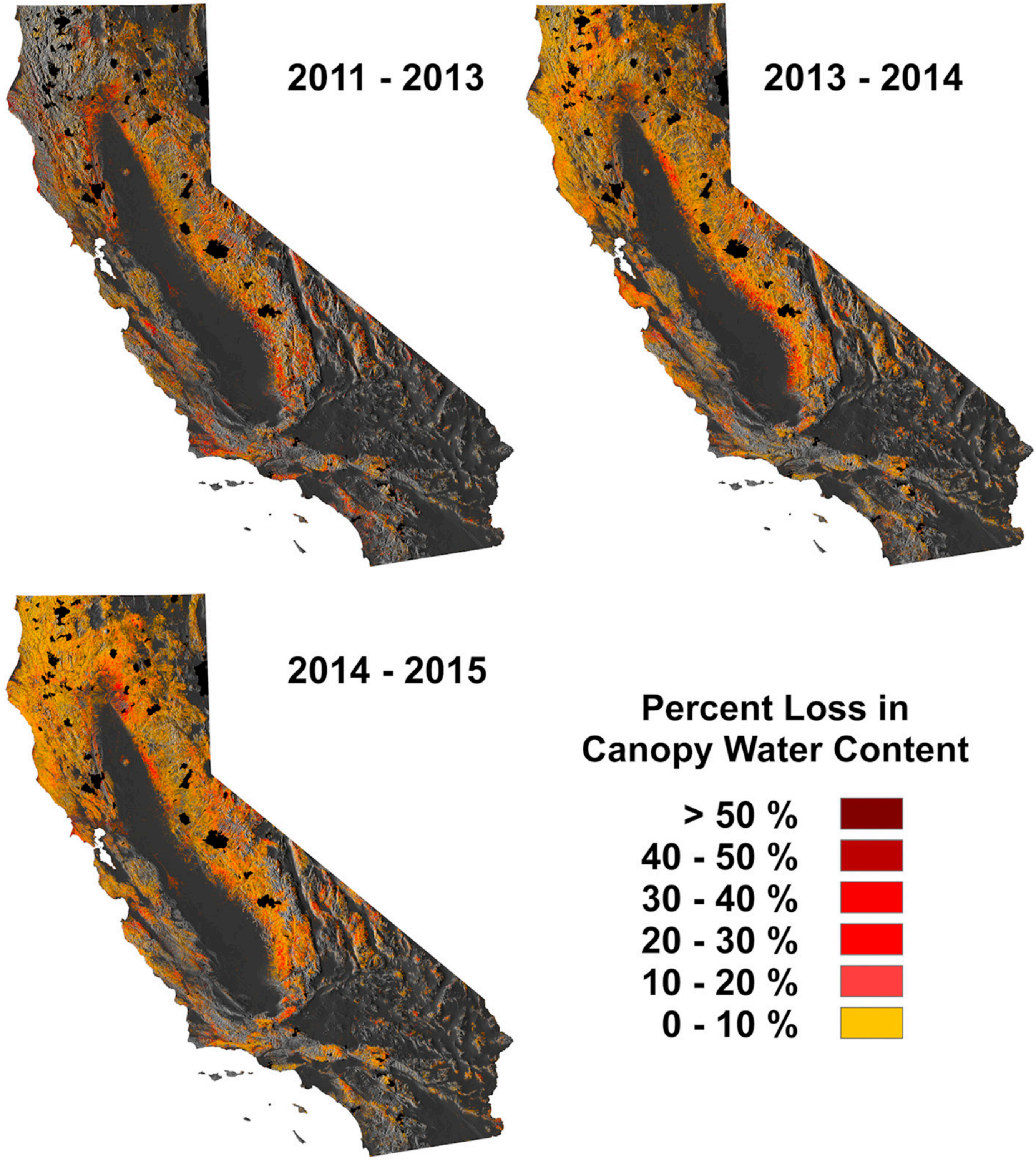

Fig. 3. Forest canopy water loss from 2011 to 2013, 2013 to 2014, and 2014 to 2015. Black areas indicate fire extents reported between 2011 and 2015 by the US Forest Service (31).

The statewide model for August 2015 indicated local- to regional-scale gradients in forest canopy water content (Fig. 2 and *SI Appendix*, Figs. S7–S9). The lowest modeled CWC values (<1.0 L/m^2) were observed in southern Californian forests as well as in lower elevation forests encircling the Central Valley. This included lower elevations of the Sierra Nevada Mountains. Additional low-CWC forests were modeled on slopes above forested drainages and river valleys, as well as in extensive swaths throughout much of the state's wildland-urban interface.

Forest Canopy Change 2011–2015. Statewide retrospective analyses revealed major changes in forest CWC between 2011 and 2015 (Fig. 3). We emphasize the importance of drought in the following results, but note that changes in CWC integrate the effects

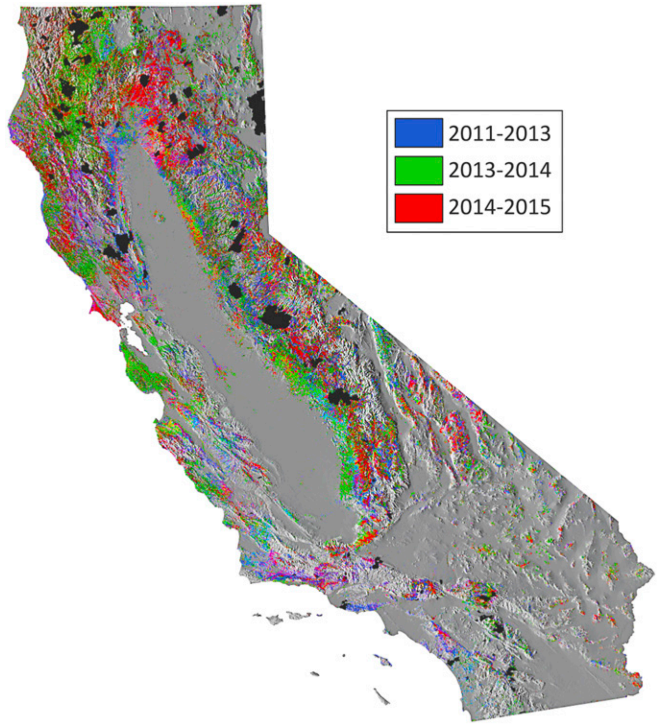

Fig. 4. The geography of forest canopy water loss from 2011 to 2015, partitioned spatially by onset period of observation. Only water losses of at least 5% are displayed. Black areas indicate fire extents reported between 2011 and 2015 by the US Forest Service (31).

of drought, widespread insect damage, and high temperatures (3, 31). Our results exclude all reported burned areas mapped between 2011 and 2015 by the US Forest Service (31), so as not to conflate CWC loss caused by fire damage. We also generated a map showing the period in which CWC decreased by at least 5% (Fig. 4 and *SI Appendix*, Figs. S10–S12). This map reveals the spatially progressive nature of forest canopy response to drought through time.

Results indicated that the area of forest negatively impacted in the 2011–2013, 2013–2014, and 2014–2015 periods was 4.0, 6.1, and 6.6 million ha, respectively (Figs. 3 and 4 and *SI Appendix*, Fig. 5*A*). From 2011 to 2013, many of the lower-elevation forests and woodlands encircling California's Central Valley underwent CWC losses (Fig. 4, blue). By 2014, additional water loss was found in lowland and foothill forest settings, such as the Santa Cruz Mountains (Fig. 4, green). By 2015, much more extensive drought-related forest canopy water loss was observed at higher elevation, well above the zones of initial water loss (Fig. 4, red).

To place the CWC results in the context of potentially at-risk trees, we mapped stem densities provided in 5,565 US Forest Service Forest Inventory and Analysis (FIA) field plots (32) to estimate the maximum number of "large" trees (≥12.7 cm diameter at breast height) affected by drought-related factors (*SI Appendix*, Figs. S13 and S14). From 2011 to 2013, the forested area of 4.0 million ha contained up to 283 million large trees that showed a measurable degree of water loss (Fig. 5*B*). In the 2013–2014 interval, 6.1 million ha of forest with up to 507 million large trees were measurably affected by drought-related factors. In the 2014–2015 interval, 6.6 million ha and up to 565 million large trees were negatively affected. Although we emphasize that these statistics do not represent mortality, they do point to rapid increases in the vulnerability of millions of trees that were physically and physiologically affected by drought and related factors.

We combined the multiyear results from Fig. 3 into a single map of progressive canopy water stress indicating the cumulative water loss for forests in California, as the sum of percent water losses from 2011 to 2015 (Fig. 6 and *SI Appendix*, Figs. S15–S17). Based on this map, we estimate that 10.6 million ha and up to 888 million large trees underwent progressive, directional decreases in CWC between 2011 and 2015. Of this amount, a total forest area of 5.4 million ha, comprising up to 412 million large trees, decreased in canopy water content by at least 10%. Losses of greater than 30% CWC, a threshold we view as severe based on aircraft videography and visual observations, covered a cumulative area of 1 million ha comprised of up to 58 million large trees.

Although it is conceptually straightforward to link canopy water loss to suppressed growth or carbon uptake in forests (8), it is more challenging to convert maps of CWC loss to estimates of tree mortality. For example, the range of potential mortality responses at 10% CWC loss on a hectare scale is a follows: a 10% decrease in average CWC could represent mortality of up to 8 trees per hectare at FIA's median California forest stand density of 80 large trees per hectare. On the other hand, 10% CWC loss could be spread among all trees in a hectare, thereby representing a measurable, but likely nonlethal, amount of water loss or leaf area reduction among all trees. However, very few regions selected for airborne CWC mapping showed such evenness in canopy water content by 2015 (Fig. 1). Moreover, analysis of aircraft-based CWC in 2015 against the retrospective, progressive water stress map (Fig. 6) indicated that water losses were strongly associated with tree-scale changes in water content (*SI Appendix*, Table S3). Based on these observations and analyses, we believe that CWC decreases of more than 10% on a hectare basis represent, at a minimum, a major suppression of productivity and reductions in canopy leaf area, and more likely indicate a loss of multiple trees per hectare.

We further interpreted the progressive water loss results based on the US Geological Survey LANDFIRE land-cover classification (*SI Appendix*). From 2011 to 2015, vegetation types showing large declines in CWC (>15%) included lowland mixed conifer-oak, particularly pine-dominated areas, chaparral woodlands, as well as trees in shrubland ecosystems (*SI Appendix*, Table S2). Note again that our minimum canopy height cut-off was 2 m, including in areas classified as shrubland. Major CWC decreases were observed in forests comprised of coastal redwoods in the lowlands, and at higher elevations pinyon-juniper, lodgepole pine,

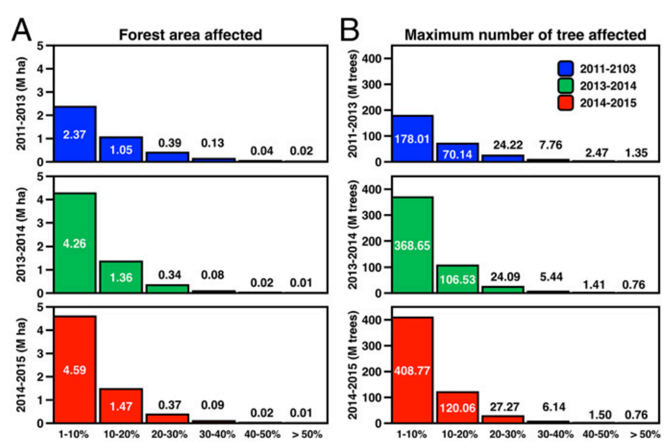

Fig. 5. (*A*) Mapped forest areas of decreases in canopy water content between 2011–2013, 2013–2014, and 2014–2015. (*B*) Estimated maximum number of trees (≥12.7 cm or 5 inches diameter at breast height) affected for each observation interval.

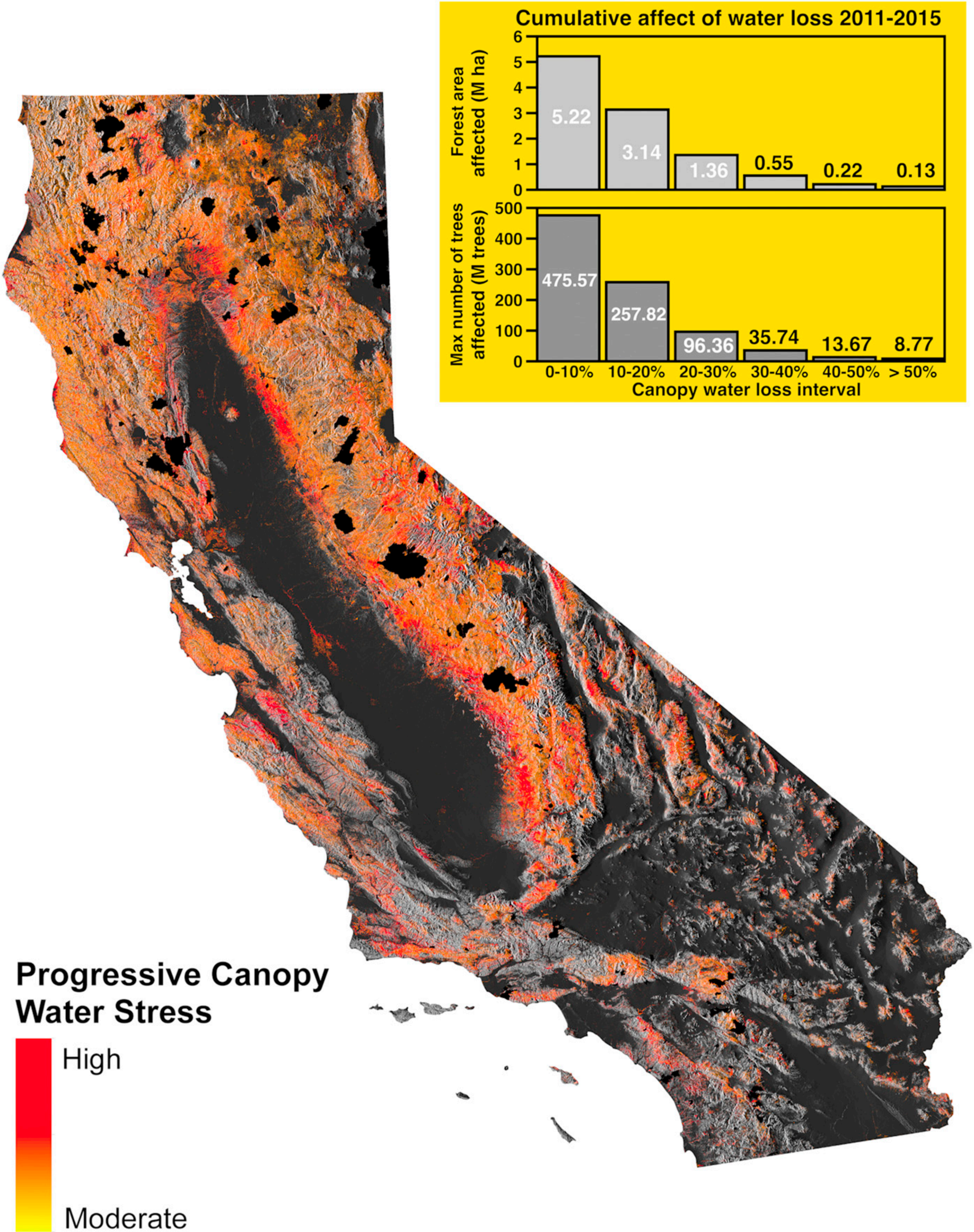

Fig. 6. Progressive forest canopy water stress for the years 2011–2015, computed as the total percentage CWC loss for the study period. Inset graph indicates the mapped forest area and estimated maximum number of trees (≥12.7 cm or 5 inches diameter at breast height) affected in differing CWC loss classes. Black areas indicate fire extents reported between 2011 and 2015 by the US Forest Service (31).

red fir, and black oak forests underwent widespread water losses. Only the highest-elevation forests and patches of lower-elevation forests and woodland types showed less (but still measurable) losses in CWC.

Forest Monitoring in a Changing Climate. To our knowledge, our results are the first to reveal progressive forest canopy water loss resulting in highly suppressed canopy water content in many regions of California. By August 2015, much of the state had undergone a measurable decrease in forest CWC since 2011. Over approximately the same time period, low-altitude visual mapping studies conducted by the US Forest Service estimated that roughly 27 million trees died in California forests (7, 33, 34). Major differences in mapping approach preclude a direct comparison of our method to aerial tree counts: Aerial surveys of brown and leafless trees suggest increasing mortality rates over time, whereas our modeled changes in canopy water content serve more of a prognostic role in terms of potential mortality. Nonetheless, map-to-map comparisons indicate a similar overall geographic pattern of canopy water loss (Fig. 6) and mortality (7, 33).

Importantly, our measurements reveal far higher levels of drought-affected forest than can be assessed using visual mapping approaches. We found massive areas of progressive canopy water stress that are geographically aligned with a growing population of observed dead trees. Moreover, if drought continues or reoccurs, there exists a pool of trees spread over millions of hectares of forest that may undergo sufficient CWC loss to result in death. Based on rates of CWC change observed during the drought (Fig. 5), this pool could increase into the hundreds of millions of trees.

Given the wide variety of forest and woodland environments found throughout California, and their variable CWC losses during the 2012–2015 drought, repeated airborne and satellite surveys will be needed to assess longer-term impacts. By combining CWC monitoring with field inventory, it should be possible to develop a capability to predict mortality. Until then, our approach uniquely identifies trees and landscapes of changing vulnerability as climate conditions evolve over time.

CWC monitoring yields spatially explicit information to support innovations in forest conservation, management and resource policy development at multiple scales. The options vary depending upon the scale-dependent technological steps developed and presented here. High-resolution, aircraft-based CWC measurements provide new data on millions of hectares of forest and generate detail on a tree-by-tree basis (Fig. 1). Potential applications of HiFIS data include implementation of prescribed fire, firebreaks, and other fire-management approaches, hazardous tree removal, ecological corridor and habitat management, and watershed management. At the broad state level, the 30-m resolution models reveal the full extent and depth of impact of drought on California's entire forest canopy. The findings strongly suggest that if drought continues, even with a potential temporary reprieve via a 2015–2016 El Niño (35), we can expect continuing forest change at the regional scale. Long-term resource policy and decision-making efforts may consider such impacts on forest resources, such as by assessing geographically explicit increases in carbon emissions where tree mortality occurs, versus increases in carbon sequestration following tree species migration (e.g., higher elevations). Planning for corridors of species migration in California, such as by expanding protected areas and limiting infrastructural development, is one example strategic use of the new information derived from imaging spectroscopy.

In the context of forest management and resource decision-making, current mainstream satellite technologies provide information only on forest cover, deforestation, and other physical disturbances to forest canopies (36). We currently lack a mission to place a high-fidelity imaging spectrometer into Earth orbit. Such a device will deliver continuous measurements of vegetation canopy water content, along with several other Earth surface chemicals (22, 37). The NASA HyspIRI imaging spectrometer remains in a premission phase of study (11), yet it lacks a clear plan or schedule for deployment. Such a mission could greatly enhance our ability to measure, monitor, and map changes in biospheric composition and function in the face of climate change.

Methods

To assess the effect of progressive drought on California forests, HiFIS and LiDAR data were collected using the Carnegie Airborne Observatory (26). The CAO sensor package includes a dual-laser waveform LiDAR system and a HiFIS that measures in the 380- to 2,510-nm wavelength range (*SI Appendix*). The CAO is able to collect up to 6 ha/s of data during flight. Even at this rapid rate it is unrealistic to provide wall-to-wall coverage of California's ∼13.4 million ha of forest. Moreover, even complete coverage would provide only an instantaneous view in time of CWC. Instead, our approach builds upon established methods for using noncontinuous airborne data to train a portfolio of geographically contiguous data to generate statewide geographic models of forest CWC (*SI Appendix*).

ACKNOWLEDGMENTS. This study was supported by the David and Lucile Packard Foundation. The Carnegie Airborne Observatory is currently supported by the Avatar Alliance Foundation, John D. and Catherine T. MacArthur Foundation, Mary Anne Nyburg Baker and G. Leonard Baker Jr., and William R. Hearst III.

1. Robeson SM (2015) Revisiting the recent California drought as an extreme value. *Geophys Res Lett* 42(16):6771–6779.
2. Brown EG (2015) *State of California Proclamation of a State of Emergency* (Executive Department, State of California, Sacramento, CA).
3. Williams AP, et al. (2015) Contribution of anthropogenic warming to California drought during 2012-2014. *Geophys Res Lett*, 42(16):6819–6828.
4. Diffenbaugh NS, Swain DL, Touma D (2015) Anthropogenic warming has increased drought risk in California. *Proc Natl Acad Sci USA* 112(13):3931–3936.
5. Allen CD, et al. (2010) A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *For Ecol Manage* 259(4):660–684.
6. Chornesky EA, et al. (2015) Adapting California's ecosystems to a changing climate. *Bioscience* 65(3):247–262.
7. USFS (2015) *2015 Forest Health Protection Arial Detection Survey*. Available at www.fs.usda.gov/detail/r5/forest-grasslandhealth/. Accessed November 1, 2015.
8. Asner GP, Nepstad D, Cardinot G, Ray D (2004) Drought stress and carbon uptake in an Amazon forest measured with spaceborne imaging spectroscopy. *Proc Natl Acad Sci USA* 101(16):6039–6044.
9. Shugart HH, et al. (2015) Computer and remote-sensing infrastructure to enhance large-scale testing of individual-based forest models. *Front Ecol Environ* 13(9): 503–511.
10. Schimel DS, Asner GP, Moorcroft PR (2013) Observing changing ecological diversity in the Anthropocene. *Front Ecol Environ* 11(3):129–137.
11. Lee CM, et al. (2015) An introduction to the NASA Hyperspectral InfraRed Imager (HyspIRI) mission and preparatory activities. *Remote Sens Environ* 167:6–19.
12. Curran PJ (1989) Remote sensing of foliar chemistry. *Remote Sens Environ* 30:271–278.
13. Asner GP, Martin RE, Anderson CB, Knapp DE (2015) Quantifying forest canopy traits: Imaging spectroscopy versus field survey. *Remote Sens Environ* 158(0):15–27.
14. Serbin SP, Singh A, McNeil BE, Kingdon CC, Townsend PA (2014) Spectroscopic determination of leaf morphological and biochemical traits for northern temperate and boreal tree species. *Ecol Appl* 24(7):1651–1669.
15. Clark RN, et al. (2003) Imaging spectroscopy: Earth and planetary remote sensing with the USGS Tetracorder and expert systems. *J Geophys Res Planets* 108(5131):1–44.
16. Chaves MM, et al. (2002) How plants cope with water stress in the field. Photosynthesis and growth. *Ann Bot (Lond)* 89(Spec No):907–916.
17. Metcalfe DB, et al. (2008) The effects of water availability on root growth and morphology in an Amazon rainforest. *Plant Soil* 311(1-2):189–199.
18. Farooq M, Wahid A, Kobayashi N, Fujita D, Basra SMA (2009) Plant drought stress: Effects, mechanisms and management. *Sustainable Agriculture*, eds Lichtfouse E, Navarrete M, Debaeke P, Souchere V, Alberola C (Springer, The Netherlands), pp 153–188.
19. Meir P, et al. (2009) The effects of drought on Amazonian rain forests. *Amazonia and Global Change, Geophysical Monograph Series*, eds Keller M, Bustamante M, Gash J, Silva Dias P (American Geophysical Union, Washington, DC), Vol 186, pp 429–449.
20. Nepstad DC, et al. (2002) The effects of partial throughfall exclusion on canopy processes, aboveground production, and biogeochemistry of an Amazon forest. *J Geophys Res* 107(D20):1–18.
21. Vourlitis GL, et al. (2008) Energy balance and canopy conductance of a tropical semi-deciduous forest of the southern Amazon Basin. *Water Resour Res* 44(3):W03412.
22. Ustin SL, Roberts DA, Gamon JA, Asner GP, Green RO (2004) Using imaging spectroscopy to study ecosystem processes and properties. *Bioscience* 54(6):523–534.

23. Gao B-C, Goetz AFH (1990) Column atmospheric water vapor and vegetation liquid water retrievals from airborne imaging spectrometer data. *J Geophys Res* 95(D4): 3549–3564.
24. Green RO, Painter TH, Roberts DA, Dozier J (2006) Measuring the expressed abundance of the three phases of water with an imaging spectrometer over melting snow. *Water Resour Res* 42(10):W10402.
25. Asner GP, et al. (2007) Carnegie Airborne Observatory: In-flight fusion of hyperspectral imaging and waveform light detection and ranging for three-dimensional studies of ecosystems. *J Appl Remote Sens* 1:013536.
26. Asner GP, et al. (2012) Carnegie Airborne Observatory-2: Increasing science data dimensionality via high-fidelity multi-sensor fusion. *Remote Sens Environ* 124(0): 454–465.
27. Mascaro J, et al. (2014) A tale of two "forests": Random forest machine learning AIDS tropical forest carbon mapping. *PLoS One* 9(1):e85993.
28. Asner GP (2009) Tropical forest carbon assessment: Integrating satellite and airborne mapping approaches. *Environ Res Lett* 4(3):034009.
29. Ustin S, et al. (1996) Estimating canopy water content of chaparral shrubs using optical methods. *Summaries of the Sixth Annual JPL Airborne Earth Science Workshop*, ed Green RO (NASA Jet Propulsion Laboratory, Pasadena, CA), pp 235–238.
30. Ceccato P, Flasse S, Tarantola S, Jacquemoud S, Gregoire JM (2001) Detecting vegetation leaf water content using reflectance in the optical domain. *Remote Sens Environ* 77(1):22–33.
31. USDA (2015) *US Forest Service Fire Detection Maps*. Available at activefiremaps.fs.fed.us/. Accessed November 1, 2015.
32. USDA (2008) *Forest Inventory and Analysis Program*. Available at www.fia.fs.fed.us. Accessed November 1, 2015.
33. USFS (2015) *1014 Aerial Survey Results: California*. Available at www.fs.usda.gov/detail/r5/forest-grasslandhealth. Accessed November 1, 2015.
34. USFS (2013) *2012 Aerial Survey Results: California*. Available at www.fs.usda.gov/detail/r5/forest-grasslandhealth. Accessed November 1, 2015.
35. NOAA (2015) *El Niño/Southern Oscillaiton (ENSO) Diagnostic Discussion* (National Weather Service, College Park, MD).
36. GOFC-GOLD (2008) *Reducing Greenhouse Gas Emissions from Deforestation and Degradation in Developing Countries: A Sourcebook of Methods and Procedures for Monitoring, Measuring and Reporting* (Office of GOFC-GOLD Program, Alberta, Canada).
37. Kokaly RF, Asner GP, Ollinger SV, Martin ME, Wessman CA (2009) Characterizing canopy biochemistry from imaging spectroscopy and its application to ecosystem studies. *Remote Sens Environ* 113(0):S78–S91.