California Environmental Protection Agency

Air Resources Board

Technical Documentation for

California's 2001-2010
Forest and Other Natural Lands
Carbon and Emission Inventory

State of California
Air Resources Board
Air Quality Planning and Science Division

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1. Background

Carbon Uptake and Loss

Trees and other green plants remove CO_2 from the atmosphere via photosynthesis. Light energy is captured by chlorophyll in plant cells and used to convert water, carbon dioxide, and minerals into oxygen and energy-rich organic compounds (carbohydrates). The total amount of energy stored into carbohydrates through photosynthesis is called Gross Primary Production (GPP). GPP is generally expressed as a mass of carbon per unit area per unit of time. Plants use some of their carbohydrates for energy through cellular respiration, and that process releases carbon back to the atmosphere as CO_2. About half of GPP is respired by plants, the remaining carbohydrates being used to build plant tissues (e.g., roots, stems, leaves, seeds). These tissues constitute the plant biomass and, as they die, dead biomass. GPP minus plant respiration is called Net Primary Production (NPP), and comprises the amount of living and dead biomass produced per unit area per unit of time. The carbon found in carbohydrates within plant tissues is sequestered away from the atmosphere for a period of time, until it is later released back into the atmosphere: rapidly through disturbance such as combustion, or slowly via decomposition. NPP minus the losses from the decomposition of organic matter in dead wood, litter and soils is called Net Ecosystem Production (NEP). NEP minus further carbon losses from disturbance (e.g. fire, harvesting, land-clearing), is referred to as Net Biome Production (NBP).

Carbon Pools

The concept of reservoirs or pools is useful to keep track of the fate of the carbon that has been removed from the atmosphere by plants. The United Nations Framework Convention on Climate Change (UNFCCC) defines reservoirs as "components of the climate system where a GHG or a precursor of a GHG is stored" (UNFCCC 2014). The carbon reservoirs or pools in a forested landscape include: the Above-Ground Live (AGL)(trunks, stems, foliage) and Below-Ground Live vegetation pools (roots); the dead organic matter (DOM) pools (standing or downed dead wood, litter); and the soil organic matter (SOM) pool. Natural and working land carbon and greenhouse gas (GHG) inventories also give special consideration to a forest biomass pool called Harvested Wood Products (HWP). Over time, carbon is transferred among these different pools, including the atmosphere which exchanges carbon via photosynthesis, respiration, decomposition and combustion (Figure 1). For example, when a tree is harvested a portion of its carbon is transferred from the live tree pool to the harvested wood product pool; during a fire some of the carbon contained in live or dead wood pools is released to the atmosphere as CO_2 (and as other GHG and non-GHG gases, and as particulate matter) while other carbon remains on the land surface in the form of unconsumed fuel, killed vegetation, cinders or ash.

Figure 1. Diagram of land carbon stocks and transfers among stocks

Source: Heath et al. 2003
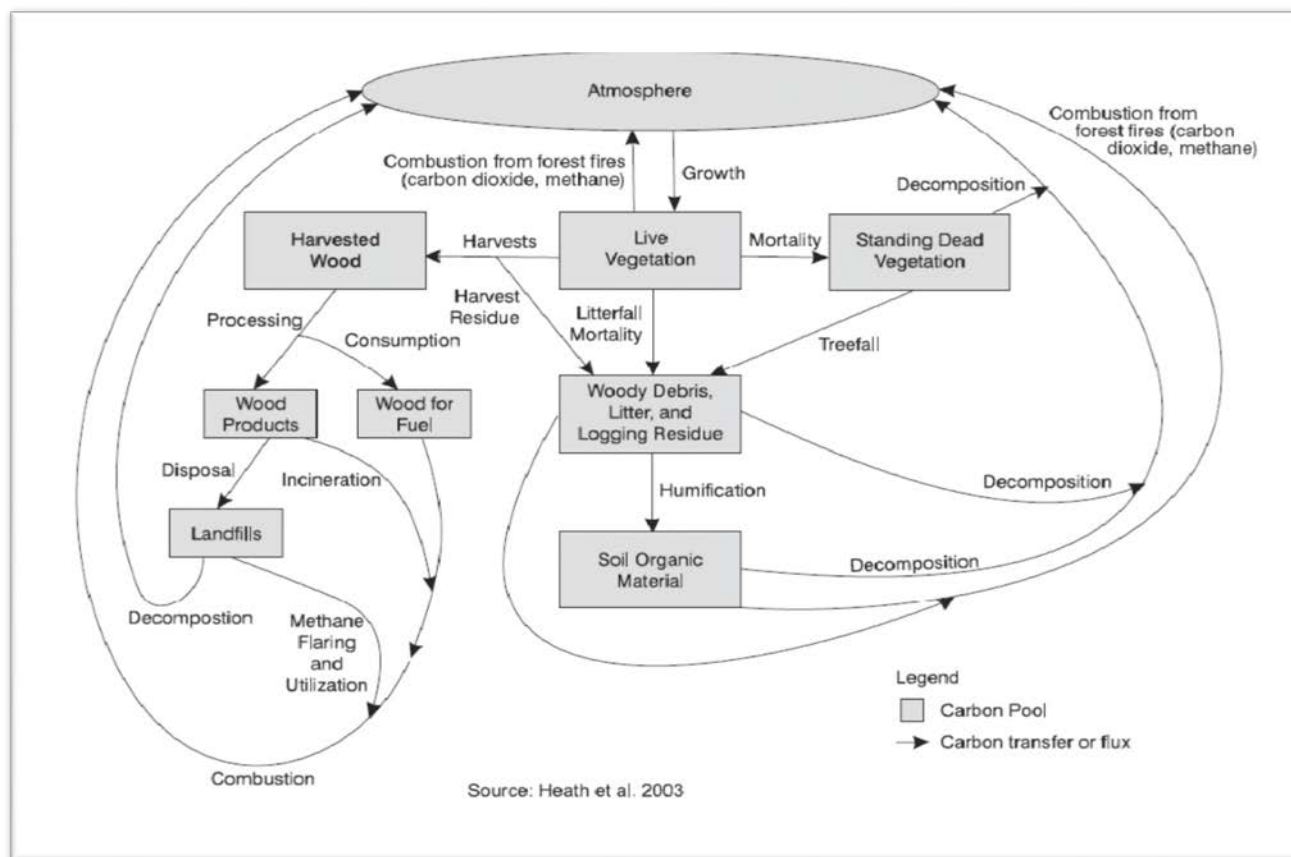
IPCC Accounting Framework

   The Intergovernmental Panel on Climate Change (IPCC) framework for land-based inventory involves quantifying carbon stocks and change within land categories that remain the same category over the time period of analysis, and land categories that change to a different category (Figure 2). IPCC land categories include Forest Land, Grassland, Wetlands, Settlements (urban/developed), Cropland, and Other Land (IPCC 2006). The IPCC definition of Forest Land includes land dominated by shrubs. Other Land includes rock, bare soil, barren or sparsely vegetated land, snow/ice, and land areas that do not fall within the other five land categories. By convention, changes in carbon stocks associated with a land change to a new category are reported in the new category. For example, the carbon stock change associated with converting cropland to urban land is reported in the Settlements category.

Figure 2. Diagram of IPCC land and stock change categories
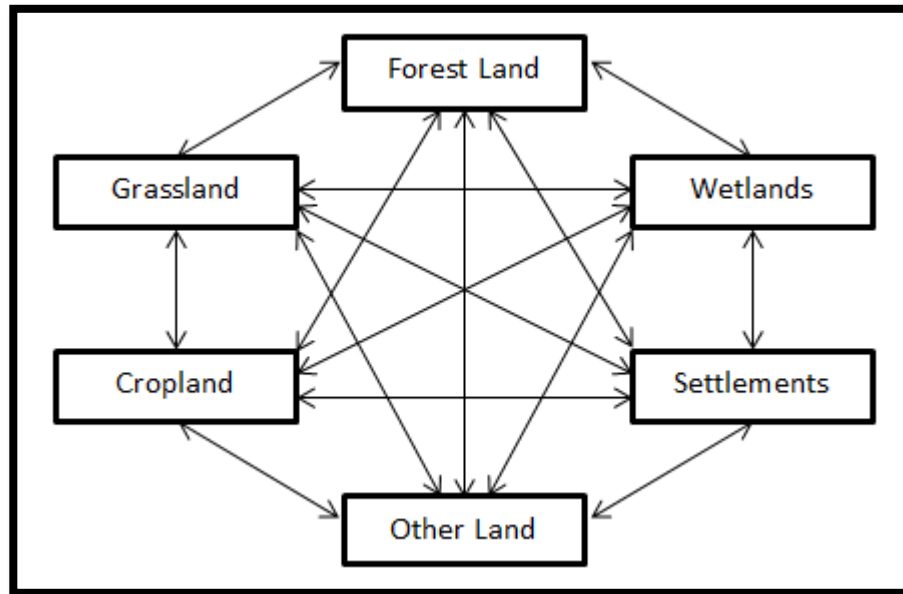
   The IPCC provides three framework options for inventory reporting. Each option prescribes specific system boundaries. (1) The stock-change approach (SCA) reports changes in ecosystem carbons stocks and wood products in the reporting country, including imported wood products. (2) The production approach (PA) reports changes in ecosystem carbon stocks and wood products produced in the reporting country. Changes in wood products exported from the producing country are also reported, while products imported to the reporting country are not counted. (3) The atmospheric flow approach (AFA) accounts for carbon fluxes to/from the atmosphere for lands and wood products pools, including imported products. The AFA includes in its estimate the exchange of carbon with the atmosphere due to changes in carbon stocks in forests and other lands, and carbon releases to the atmosphere associated with harvested wood. Ecosystems also emit N_2O and CH_4 through soil microbial processes and the combustion of organic matter. ARB uses the AFA because the system boundaries are most consistent with how emissions from anthropogenic sources are accounted in the GHG inventory.

   The IPCC also provides two accounting methods for estimating the exchange of carbon between the atmosphere and the land, and carbon transfers among other pools (IPCC 2006). (1) The gain-loss method (sometimes described as process-based) subtracts carbon losses from carbon gains, to estimate the net balance of additions to and losses from a pool. (2) The stock-difference method estimates the difference in carbon stocks (pools) at two points in time. IPCC inventory guidance conceives a hierarchy or tier of methods, ranging from the simplest to use (Tier 1), to higher order methods (Tier 3) featuring custom measurement systems and/or models "repeated over time and driven by high-

resolution activity data and disaggregated at the sub-national level." For this 2001-2010 analysis of land carbon stock and stock change, ARB is using the stock-difference method. Because this method uses California-specific data repeated over time, it would be considered a Tier 3 method under the IPCC inventory framework.


2. Methodology

Forests and Other Lands Biomass

ARB estimates for biomass, carbon stocks and stock change on forests and other lands for 2001 – 2010 are based on sources and methods developed under a contract with the University of California (Battles et al. 2013), reported in Gonzalez et al. (2015), and developed further under a follow-up contract (Saah et al. 2016). The methods combine geospatial vegetation and disturbance activity data with tabular data from georeferenced forest plots, reference databases and literature. Thirty meter resolution geospatial data from the federal LANDFIRE program include vegetation species composition (existing vegetation type, EVT and vegetation order [tree, shrub, or grass/herbaceous-dominated]) and structure (canopy height class EVH, and canopy cover class EVC) for 2001 and 2010, and disturbance activity (fire, harvest, thinning, etc.) throughout the 2001 – 2010 period (Ryan and Opperman 2013). Field data include biomass densities (Mg ha^{-1}) calculated from regional allometric equations for the above- and below-ground live tree and standing dead tree pools, and modeling of understory vegetation, down dead and litter pools in 3,623 georeferenced forest plots maintained by the Forest Inventory and Analysis (FIA) program of the USDA Forest Service (Battles et al. 2013). Biomass densities for shrub-dominated lands were compiled from field data reported in the LANDFIRE reference database (LFRDB) and in published literature. For land types dominated by non-woody vegetation such as grassland, wetlands, and sparsely vegetated lands, biomass densities were derived from NPP estimated from the Moderate Resolution Imaging Spectroradiometer (MODIS product MOD17A). ARB refinements to the methods include accounting for a decadal carbon increment associated with live tree growth undetected by the satellite-derived LANDFIRE products, post-harvest carbon persisting in wood products, and development of default biomass densities for croplands and selected categories of developed lands.

Biomass densities (Mg C ha^{-1}) and total biomass (Mg C pixel^{-1}) in forests and other lands for 2001 and 2010 were estimated at 30 meter spatial resolution using regression equations designed to predict biomass and carbon stocks as functions of LANDFIRE vegetation attributes EVT, EVC and EVH (Gonzalez et al. 2015). The method assumes the carbon content of biomass is 0.47 g C g^{-1} biomass (± 0.0235 g C g^{-1} biomass)(Gonzalez et al. 2015). In order to report carbon stocks and change by IPCC categories, LANDFIRE EVTs for California

(n = 168) were assigned to IPCC land categories. One hundred and thirty-two EVTS were assigned to the Forest Land category. Of these, eighty-nine were tree-dominated and forty-three were shrub-dominated types, according to the LANDFIRE attribute vegetation Order. The remaining thirty-six EVTs were assigned to the Grassland (17), Other Land (15) and Wetlands (4) categories.

Stock change in the AGL and Total pools (live and dead pools combined, not including soil carbon) for the 2001 - 2010 analysis period was estimated by raster subtraction. For many areas that were dominated by trees in both 2001 and 2010, LANDFIRE data did not report changes in forest canopy height or canopy cover. The "non-detection" of forest canopy growth is due in part to the ordinal nature of LANDFIRE canopy cover and height classes. For canopy cover, LANDFIRE defines ten classes that increase in even steps of 10%, while LANDFIRE defines five canopy height classes of 0-5, 5-10, 10-25, 25-50, and >50 meters. If over the analysis period the average height or cover at a location changed but did not cross into the next class, the method would record no change in biomass. Because tree growth occurs slowly relative to the span of the analysis period, the method can underestimate biomass changes due to growth within a cover or height class. Consequently, the method is sensitive to abrupt changes associated with disturbance while less sensitive to slow changes associated with growth, particularly in mature forests. Tree re-measurement data reported in FIA database version 6.0 (released October 2, 2014) indicated that over a decade, live tree biomass increased statewide on average by 6% (Gonzalez et al. 2015). In order to account for the carbon increment associated with live tree growth in areas dominated by trees in both 2001 and 2010 and where LANDFIRE did not detect change, an adjustment factor was applied to the 2010 above-ground live stocks (Saah et al. 2016). The adjusted 2010 rasters for AGL and Total were used together with the 2001 rasters to evaluate stock change (Figure 3). Stocks and stock changes were tabulated by IPCC reporting categories.

Figure 3. Workflow diagram (stock change attribution not shown)
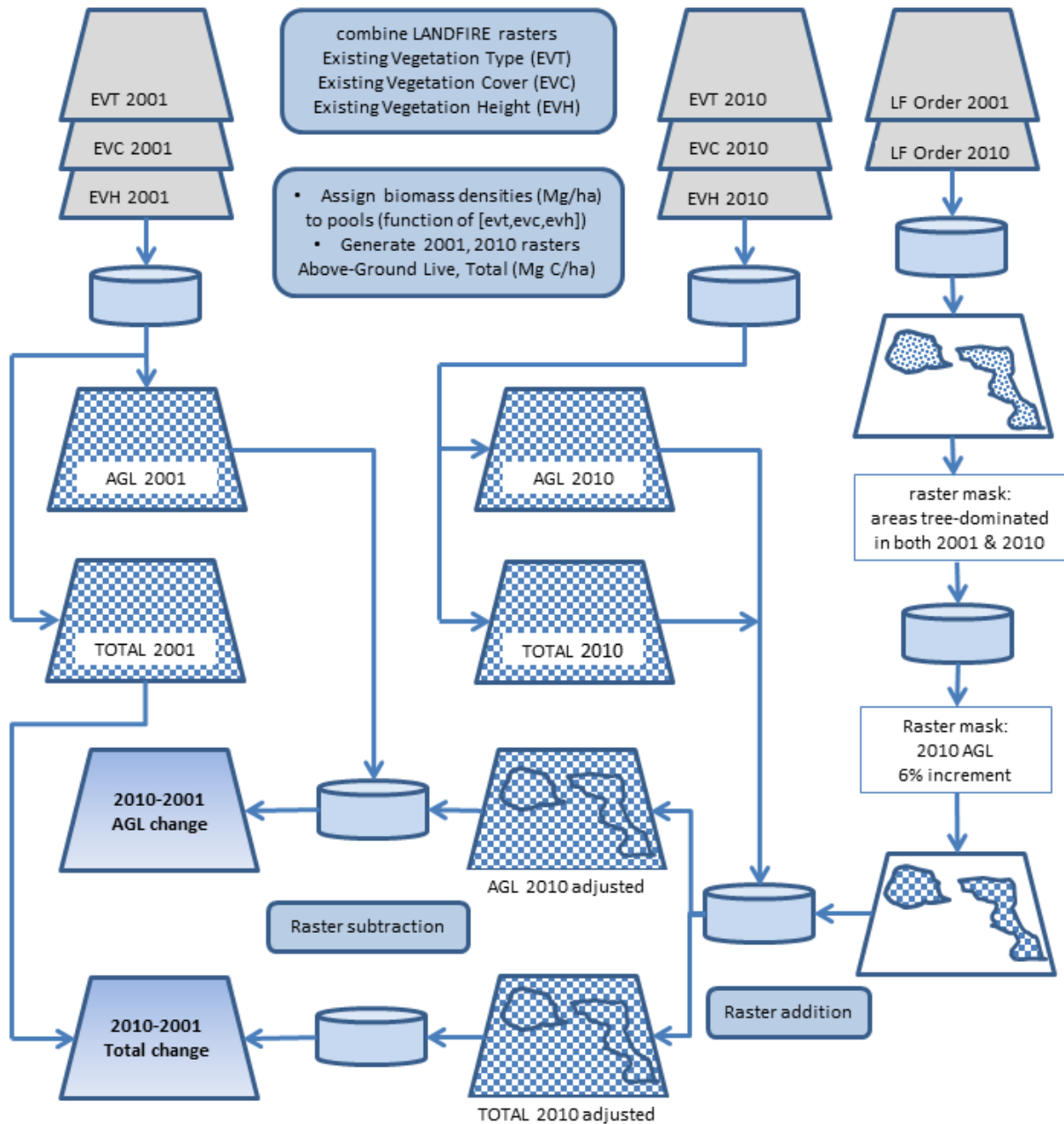
Stock Change Attribution: Introduction

IPCC inventory guidance provides for stock change attribution by selected disturbance types. These include biomass burning (IPCC category 3C1) and wood harvest (IPCC category 3D1). LANDFIRE geospatial data on disturbance activity was used to locate areas where fires and harvest related activities occurred during 2001-2010. LANDFIRE fire categories include wildfires

(Wildfire), prescribed wildland burning (Rx fire), and Wildland Fire Use (WFU). Harvest related categories include Clearcut, Thinning, Harvest, Mastication and Other Mechanical. Stock change attribution was achieved by spatial overlay of disturbance areas upon the stock change layer (obtained from raster subtraction). There were areas where fire and harvest "footprints" spatially overlapped, potentially confounding stock change attribution. Moreover, wildfires were spatially extensive, whereas harvest-related activities had limited spatial extent. (More information on the spatial extent of wildfires is discussed in the Data Sources section (Figure 4) and the Results section (Table 4).) In order to attribute stock change to a single disturbance type and to avoid double-counting, a calculation priority was applied: Clearcut > Harvest > Other Mechanical > Thinning > Mastication > Wildfire > WFU > Rx fire (Saah et al. 2016). The prioritization scheme principally served to avoid under-reporting stock changes attributed to harvest activities, for locations which would otherwise have been attributed to fire.

Stock Change Attribution: Fire (IPCC 3C1)

Attributing stock change to fire is complicated by the fact that fire differentially propagates and consumes live and dead vegetation, depending on environmental conditions such as fuel moisture levels, fuel loads and configuration, topography, and weather. In intense forest fires, large amounts of dead woody debris and litter are consumed. In the process some trees are killed (either by crown torching or by cambium destruction from intense fire at the ground surface) while others survive. Fires in shrub lands and grasslands typically consume nearly all above-ground biomass. Post-fire landscapes therefore feature barren areas, unburned dead fuels, killed trees, patches of intact or surviving vegetation, and re-emergent vegetation. Stock change attribution by fire was achieved by spatial overlay of LANDFIRE-mapped burn areas on the stock change layers. The fire-attributed stock changes account only for carbon contained in live and dead pools associated with the post-fire (e.g. 2010) vegetation type, and have no memory of the previous vegetation type, i.e. they do not account for potential post-fire carbon persisting in unburned fuels or in killed trees. Elsewhere, fires re-occurred during the 2001-2010 period. In these locations, it was not possible to quantify stock change associated with each fire occurrence, because stock change attribution to fire is based on a stock difference between 2001 and 2010.

Stock Change Attribution: Thinning, Harvest, Clearcut (IPCC 3D1)

Tree harvests transfer a fraction of tree carbon from live biomass to wood product pools. In the process, some carbon is lost to the atmosphere while a fraction persists for a time in solid form. Harvests and other vegetation management activities generate stock changes that are difficult to quantify using remotely-sensed data, since such activities are episodic, affect different tree size/age class cohorts, generate varied proportions of residues and

products, and because vegetation recovers at varying rates between data acquisition years.

LANDFIRE disturbance data for 2001-2010 was used to locate areas where Thinning, Clearcut, Harvest, Mastication or Other Mechanical activities occurred. Thinning is a forestry practice that reduces the number of trees per unit land area in order to improve growing conditions for remaining trees. Clearcuts remove essentially all trees in order to harvest wood and to produce exposed sites for re-planting or for natural regeneration. LANDFIRE defines Harvest as a general term for a variety of practices that involve cutting and gathering forest trees and assigns the term to locations where there is insufficient information to classify activities as either Clearcut or Thinning (Saah et al. 2016). Mastication and Other Mechanical methods are among a variety of techniques applied by land managers to reduce vegetation fuel loads and wildfire hazard in selected areas. LANDFIRE defines Mastication as the mowing or chipping of vegetation, while Other Mechanical represents a variety of vegetation fuels management techniques such as felling and piling, lop and scatter, and chaining.

Stock change estimates were retrieved for areas classified by LANDFIRE as having been clearcut, harvested, thinned, or subjected to mastication or other mechanical treatment during the 2001-2010 period. For purposes of this analysis, Mastication and Other Mechanical were assumed to generate no off-site wood products. Stock changes associated with Mastication and Other Mechanical are therefore included in the Results section (Table 4) for informational purposes, but are not components of wood product quantification (Table 5). The estimated stock changes in the AGL pool for Thinning, Clearcut and Harvest areas represent the amount of tree biomass removed from the live pool and destined for processing into wood products. The amount of wood product produced from the biomass removed from these areas was estimated using California-specific coefficients based on Stewart and Nakamura (2012) and Saah et al. (2012)(cited in Saah et al. 2016). From these, it was estimated that approximately 73% of removed carbon persists in solid form ten years after production. To estimate the net stock change associated with Thinning, Harvest and Clearcut, the estimated amount of wood product carbon persisting for ten years was deducted from the associated AGL gross stock change. The estimated net stock change of harvest represents carbon losses to the atmosphere associated with the fate of residues on-site, at mills, and with discards.

3. Data Sources

Forests and Other Lands

LANDFIRE geospatial vegetation data for 2001 (version LF 1.0.5) and 2010 (version LF 1.2.0) used in the analysis include the raster products Existing

Vegetation Type (EVT), Existing Vegetation Cover (EVC), Existing Vegetation Height (EVH), and disturbances from 2001 through 2010 (DISTYEAR). All were obtained from the LANDFIRE data distribution site. Regression equations used to estimate biomass densities (Mg ha^{-1}) for tree-dominated lands from LANDFIRE vegetation attributes EVT, EVC and EVH were developed by researchers at the University of California at Berkeley and the National Park Service (Battles et al. 2013, Gonzalez et al. 2015).

Biomass densities (Mg ha^{-1}) for land classified by LANDFIRE as shrub-dominated were compiled from the LANDFIRE reference database (LFRDB) and from published literature (Battles et al. 2013, Gonzalez et al. 2015).

For land classified by LANDFIRE as dominated by grasses and herbaceous vegetation, NPP raster data (MODIS satellite product MOD17A3, available from the USGS Land Processes Distributed Active Archive Center) was used to approximate biomass densities (Battles et al. 2013, Gonzalez et al. 2015).

Default biomass densities for Croplands and Settlements were based on compilations from literature and from spatial analysis (Saah et al. 2016).

Fire, Thinning, Harvest, Clearcut

The LANDFIRE raster product DISTYEAR was used to locate and select fire and harvest areas in the 2001-2010 period in order to attribute and tabulate stock changes according to fire or harvest (Figure 4). Estimates for carbon persisting as wood product were based on coefficients developed by Stewart and Nakamura (2012) and by Saah et al. (2012)(cited in Saah at al. 2016).

Figure 4. Disturbances by type, 2001-2010

Figure 4. Disturbances by type, 2001-2010
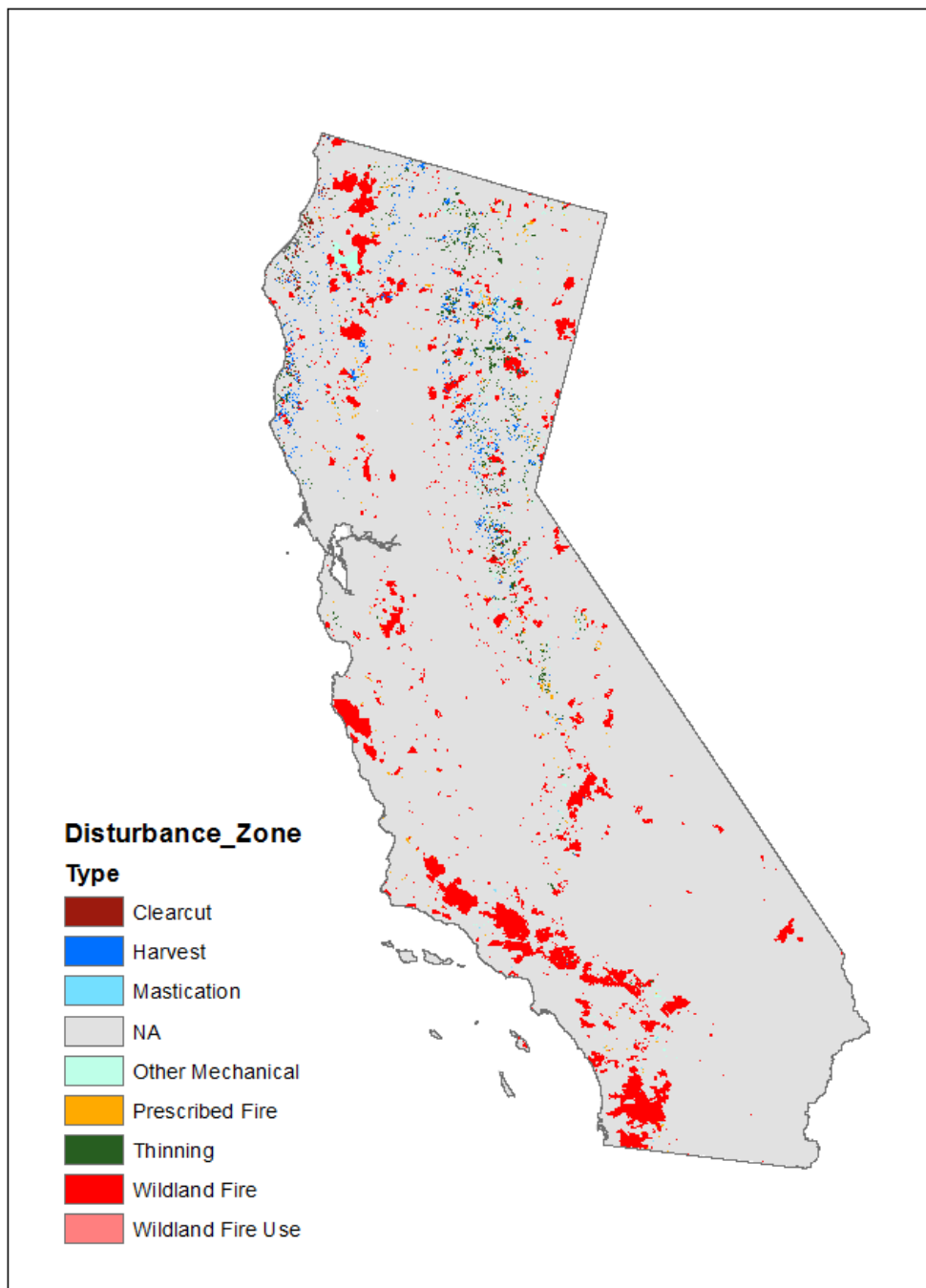
4. Results

In both 2001 and 2010, the Forest Land category contained the vast majority of statewide land carbon stock (Table 1), arrayed in mountain regions of the state (Figures 5, 6). Gonzalez and coworkers (2015) reported that the average

carbon density for the AGL pool in tree-dominated areas was 64 ± 15 Mg ha^{-1}, with Coast Redwood forests exhibiting densities of 600 ± 230 Mg ha^{-1} (mean ± 95% CI, based on Monte Carlo analysis). The 2010 statewide estimate for Forest Land AGL is in reasonable agreement with other estimates of similar vintage (Table 2). Validation against independent ground-based estimates for study areas in a Coast Redwood forest and in the Sierra Nevada, and comparisons with two remote sensing-based efforts, showed no statistically significant differences (Gonzalez et al. 2015). Overall, the AGL pool comprised approximately 35% of Total carbon (live and dead pools, not including soils) in the Forest Land category. The remaining carbon is distributed among other pools such as Understory, Standing Dead Tree, Down Dead Wood and Litter.

Table 1. Carbon stocks by IPCC land category

IPCC Land Category	2001			2010		
	Million Metric Tons Carbon (MMT C)		Area	Million Metric Tons Carbon (MMT C)		Area
	AGL[1]	Total[2]	10^3 km^2	AGL[1]	Total[2]	10^3 km^2
Forest Land[3]	916.59	2,630.73	269.3	891.79[4]	2,469.68	252.6
Grassland	3.20	16.70	27.6	5.23	27.32	41.0
Wetlands	0.18	0.93	2.2	0.00	0.00	0.00
Other Land	1.19	6.23	38.2	1.35	7.07	40.0
Sum of Land Categories	921.16	2,654.59	337.3	898.37	2,504.07	333.6
Change				-22.8	-150.5	-3.7[5]

[1]Above-Ground Live (AGL) carbon pools.

[2]All pools except soils. These include: above-ground live (trunks, stems, foliage), below-ground live (roots), standing dead, downed dead wood, and litter.

[3]IPCC definition of Forest Land includes land dominated by shrubs.

[4]Forest Land AGL in 2010 includes 6% stock increment associated with lands dominated by trees in both 2001-2010, from FIA data (growth not detected by satellite). Change does not account for carbon persisting in wood products.

[5]Land that changed to agricultural or to urban/developed land.

### Table 2. Forest land Above-Ground Live (AGL) carbon stocks: other estimates

MMT C	Source	95% Confidence Interval	Vintage
948.6[1]	ARB	± 237	2010
990	USDA-FS[2]	Not Reported	2014
1,014.4	USDA-FS[3]	± 26.3	Decadal Average 2001-2010

[1]ARB estimate converted to FIA convention (assumes biomass carbon fraction = 0.5).

[2] Forest Carbon Estimation. On-line query http://www.fia.fs.fed.us/forestcarbon/default.asp.

[3] Christensen, G. et al. 2016. California's Forest Resources: Forest Inventory and Analysis, 2001-2010. (2016) General Technical Report PNW-GTR-913. Table A2-79. Available on-line http://www.treesearch.fs.fed.us/pubs/50397.

Figure 5. Above-Ground Live (AGL) biomass (Mg C per hectare) in Forest Land, Grassland, Wetlands and Other Lands in 2010

2010 AGL biomass

MT C / hectare

- 0 - 17.3
- 17.3 - 69.4
- 69.4 - 131.3
- 131.3 - 304.8
- 304.8 - 632
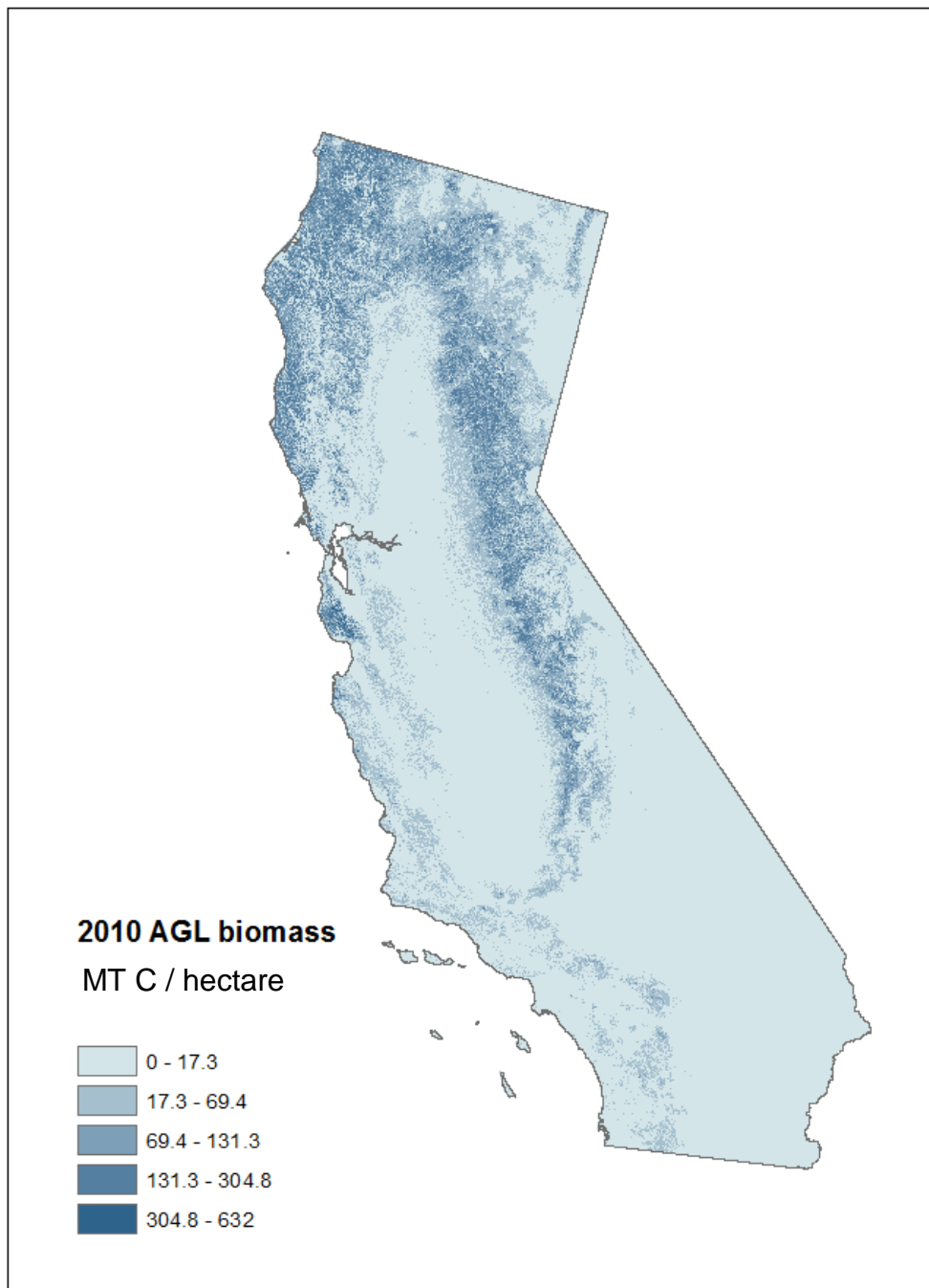
Figure 6. Total biomass (live and dead pools, not including soils, Mg C per hectare) in Forest Land, Grassland, Wetlands and Other Lands in 2010

2010 Total MTC/ha

- 0 - 35.3
- 35.3 - 133.5
- 133.5 - 235.6
- 235.7 - 518.4
- 518.4 - 1,001.5
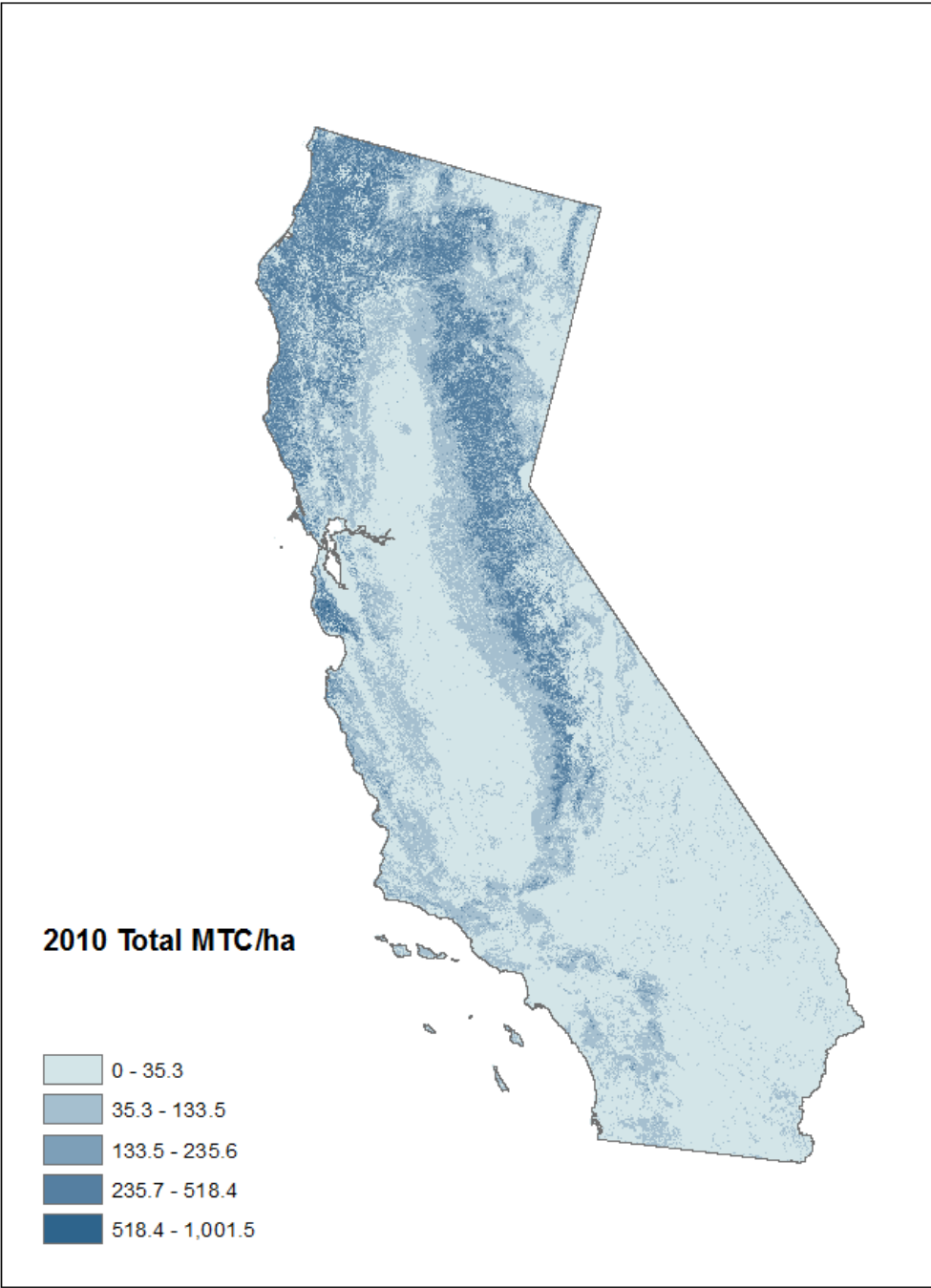
Areas that were tree-dominated in both 2001 and 2010 contributed to a net change of +17.5 MMT C in the AGL pool for the category Forest Land remaining Forest Land (IPCC 3B1a, Table 3), representing an annualized rate of approximately +1.9 MMT C yr^{-1}. However, within the Forest Land remaining Forest Land category, conversion from tree-dominated to shrub-dominated represented a net carbon loss (Gonzalez et al. 2015), and contributed to a net change of -16.89 MMT C for the Total pool (equivalent to -1.9 MMT C yr^{-1}). Overall, Forest Land area and Total carbon stocks (live and dead pools, not including soils) declined over the period, as tree- and shrub-dominated lands changed to grassland (IPCC 3B3bi) and to other land categories (Table 3; see also Table 2 in Gonzalez et al. 2015). The overall decline is consistent with other work (e.g. Powell et al. 2014 and Hicke et al. 2013, cited in Gonzalez et al. 2015; USDA Forest Service 2015).

Table 3. 2001 – 2010 Change in Land Carbon Stocks

Ecosystem budget sign convention: gains (+), losses (-). Note categories To Be Determined (TBD).

IPCC Land Category	Category Code	IPCC Category	10^6 Metric Tons Carbon (MMT C)	
			Above-Ground Live (AGL)	Total[1] (Live & Dead)
3B1 Forest Land[2]	3B1a	Forest Land remaining Forest Land	17.50	-16.85
	3B1bi	Cropland converted to Forest Land	TBD	TBD
	3B1bii	Grassland converted to Forest Land	0.38	3.45
	3B1biii	Wetlands converted to Forest Land	0.89	4.19
	3B1biv	Settlements converted to Forest Land	NA	NA
	3B1bv	Other Land converted to Forest Land	0.01	-0.07
		subtotal	*18.78*	*-9.27*
3B2 Cropland	3B2a	Cropland remaining Cropland	TBD	TBD
	3B2bi	Forest Land converted to Cropland	-1.54	-7.54
	3B2bii	Grassland converted to Cropland	-0.11	-0.19
	3B2biii	Wetlands converted to Cropland	-0.05	0.12
	3B2biv	Settlements converted to Cropland	NA	NA
	3B2bv	Other Land converted to Cropland	0.00	0.02
		subtotal	*-1.70*	*-7.59*
3B3 Grassland	3B3a	Grassland remaining Grassland	0.34	1.75
	3B3bi	Forest Land converted to Grassland	-35.44	-112.49
	3B3bii	Cropland converted to Grassland	TBD	TBD
	3B3biii	Wetlands converted to Grassland	0.03	0.14
	3B3biv	Settlements converted to Grassland	NA	NA
	3B3bv	Other Land converted to Grassland	0.00	0.00
		subtotal	*-35.07*	*-110.60*
3B4 Wetlands	3B4ai	Peatlands remaining Peatlands	NA	
	3B4aii	Flooded Land remaining Flooded Land	0.00	0.00
	3B4bi	Land converted for Peat Extraction	NA	NA
	3B4bii	Land converted to Flooded Land	NA	NA
	3B4biii	Land converted to Other Wetland	0.00	-0.01
		subtotal	*0.00*	*-0.01*
3B5 Settlements	3B5a	Settlements remaining Settlements	TBD	TBD
	3B5bi	Forest Land converted to Settlements	-0.11	-0.52
	3B5bii	Cropland converted to Settlements	TBD	TBD
	3B5biii	Grassland converted to Settlements	-0.01	-0.02
	3B5biv	Wetlands converted to Settlements	0.00	0.03
	3B5bv	Other Land converted to Settlements	0.00	0.00
		subtotal	*-0.13*	*-0.51*
3B6 Other Land[3]	3B6a	Other Land remaining Other Land	0.01	0.03
	3B6bi	Forest Land converted to Other Land	-4.65	-22.46
	3B6bii	Cropland converted to Other Land	TBD	TBD
	3B6biii	Grassland converted to Other Land	-0.02	-0.09
	3B6biv	Wetlands converted to Other Land	0.00	-0.01
	3B6bv	Settlements converted to Other Land	NA	NA
		subtotal	*-4.66*	*-22.54*
		sum MMT C[4]	*-22.8*	*-150.5*

[1] Includes Above-Ground Live (AGL) and Below-Ground Live (tree, understory, shrub, grass/herbaceous) Standing Dead, Down Dead, Litter - Not including soil.

[2] IPCC definition of Forest Land includes land dominated by shrubs. Category 3B1a AGL stock change includes 6% stock increase associated with tree growth in lands dominated by trees in both 2001 and 2010, from FIA data (growth not detected by satellite).

[3] IPCC definition of Other Land includes sparsely vegetated, barren, rock/ice, and lands that do not fall within the other 5 categories.

[4] Does not account for carbon persisting in wood products.

Of the eight LANDFIRE disturbance types evaluated, wildfires affected 3 times more area than all other disturbance types combined (Table 4). The total wildfire area in the state mapped by LANDFIRE for 2001-2010 was approximately 4% greater than an area total derived from a state geodatabase (23,871 km²)(FRAP 2016). The difference in area is attributed largely to differences in minimum fire area mapping thresholds of the two geodatabases. Spatial analysis attributed nearly 120 MMT C of stock loss from the Total carbon pool to wildfires, representing approximately 80% of the overall stock change (Table 3). Prescribed fire and WFU represented orders of magnitude smaller stock losses.

The total area affected by Thinning, Clearcut, Harvest, Mastication and Other Mechanical activities was 3 times less than the area affected by wildfire, and stock losses (not accounting for post-harvest carbon persisting in wood products) were one-fifth the magnitude of the loss represented by wildfire. Of the -10.4 MMT C gross stock change in the AGL pool attributed to Thinning, Clearcut and Harvest (Table 5), it was estimated that approximately 7.6 MMT of the removed carbon (73%) persisted in solid form over the period. Taken together, accounting for post-harvest persistent carbon results in a harvest-activities net stock change of -2.7 MMT C for the AGL pool and a corresponding -11.8 MMT C in the Total pool (Table 5). Meanwhile, stock change associated with Mastication and Other Mechanical was similar in magnitude to any of the three harvest-related activities.

Table 4. State-wide 2001-2010 stock change attribution by LANDFIRE disturbance category, total[1] carbon pool

Note: Quantities reported here are subsumed within the stock changes reported in Table 3 and are not additive.

Attribution	10⁶ Metric Tons Carbon (MMTC)[1]	km²	acres
Wildfire	-119.96	24,802.4	6,128,807.1
Thinning[2]	-7.33	3,008.9	743,515.4
Clearcut[2]	-6.14	910.0	224,865.9
Harvest[2]	-5.97	2,271.9	561,398.7
Other mechanical	-5.15	1,434.2	354,398.5
Prescribed fire (Rx fire)	-2.72	930.2	229,857.4
Wildland Fire Use (WFU)	-0.33	88.9	21,967.6
Mastication	-0.23	160.3	39,610.9

[1] Includes Above-Ground Live (AGL) and Below-Ground Live (tree, understory, shrub, grass/herbaceous) Standing Dead, Down Dead, Litter - Not including soil.

[2] Stock-loss estimate does not include carbon persisting as wood product.

Table 5. 2001-2010 stock change attribution by IPCC category

Note: Quantities reported here are subsumed within the stock changes reported in Table 3 and are not additive.

IPCC Category Code	Category Description	10⁶ Metric Tons Carbon (MMT C)	
		Above-Ground Live (AGL)	Total[1] (Live & Dead)
3C1	Biomass Burning[2] *Forest Land[3] (3C1a), Grassland (3C1c) and Other Land[4] (3C1d)*	-43.6	-123.0
3D1	*Harvest, Thinning and Clearcut*		
	Gross stock change	-10.4	-19.4
	Net stock change[5]	-2.7	-11.8

[1] Includes Above-Ground Live (AGL) and Below-Ground Live (tree, understory, shrub, grass/herbaceous) Standing Dead, Down Dead, Litter - Not including soil.

[2] Includes Wildfire, Rx Fire and WFU.

[3] IPCC definition of Forest Land includes land dominated by shrubs.

[4] IPCC definition of Other Land includes sparsely vegetated, barren, rock/ice, and lands that do not fall within the other 5 categories.

[5] Accounts for 7.6 MMT post-harvest C persisting as wood product.

Assessing stock changes associated with harvest activities behooves an evaluation between reported harvest data and LANDFIRE-based harvest estimates adjusted for land ownership type. Taking into account variation in biomass removal with respect to activity and ownership type (FRAP 2013), Saah and coworkers (2016) derived harvest volumes from the AGL stock change estimates associated with the Thinning, Clearcut and Harvest categories. The associated AGL stock changes translated to a harvest volume of approximately 11,698 million board-feet (mmbf), representing 86% of the 2001-2010 harvest volume reported by the state Board of Equalization (BoE) timber yield tax program. The authors suggest that the ostensive harvest volume underestimate may be attributed to limitations from having the LANDFIRE Harvest category serve to represent a variety of silvicultural activities which embody different stock change outcomes (e.g. group selection, variable retention, seed tree removal, and seed tree step).

5. Further Development

Forests and Other Lands: LANDFIRE Products

LANDFIRE geospatial products are evolving as the consortium expands its resource management capacity beyond wildfires. LANDFIRE is co-funded by two federal agencies (US Department of Agriculture and US Department of the Interior) and has constituents among analysts and researchers in federal and state agencies, academia, and non-governmental organizations. With each update, LANDFIRE endeavors to respond to requests for a variety of improvements. LANDFIRE vegetation mapping also abides by guidelines in the federal National Vegetation Classification System (NVCS). As a result, LANDFIRE has become a central clearinghouse of national vegetation mapping data. Consequently, continual modification of the Existing Vegetation Type (EVT) product is likely as user needs and standards change. The major source of uncertainty in ARB's land carbon quantification method for forests and other lands is EVT classification (Battles et al. 2013, Gonzalez et al. 2015). Given that LANDFIRE can assign generalized vegetation classes with greater accuracy (NatureServe 2012), new regression equations for estimating carbon densities as functions of height class, cover class and subclass (e.g., closed-canopy, evergreen forest, sparse canopy mixed forests, open canopy deciduous forest, etc.) may afford greater consistency and reduce uncertainty (Saah et al. 2016).

Stock Change Attribution: Fire

By default, the stock change estimates attributed to wildfire assume complete transfer (oxidation) of carbon to the atmosphere. Fires also emit varying

amounts of CH_4 and N_2O, depending on combustion conditions. However, not all ecosystem carbon is immediately emitted by fire: post-fire land carbon stocks in the form of residual unburned dead fuels and killed trees represent carbon pools of varying persistence. Accounting for these post-fire pools (and for other gases) could serve to better represent the timing and magnitudes of losses associated with wildfire (Hurteau and Brooks 2011).

Croplands and Settlements

IPCC guidance specifies the land categories Croplands (3B2) and Settlements (3B5) for inclusion in inventory reporting (Figure 2). Agricultural and urban areas occupy approximately 10% and 4%, respectively, of the state's land area (FRAP 2010). For these categories, ARB is developing methods to quantify land carbon stocks and change, using remotely-sensed data, ground-based data and models.

Changes in live and dead biomass pools on croplands correspond to atmospheric CO_2 removals and emissions. For annual crops, it is unclear whether the annual cycling of biomass through growth, harvest, and the disposition of post-harvest residue results in significant net carbon exchange with the atmosphere. In woody croplands (e.g., vineyards and orchards), carbon removed from the atmosphere may persist in woody tissue for decades, and orchard acreage in the state has increased in recent years (ASFMRA 2015). Meanwhile, orchards lose carbon in the form of combusted prunings and from the disposition of removed trees.

Urban areas exhibit on average 15 percent tree canopy cover and represent a type of forest where much of the state's population lives (Bjorkman et al. 2015). California's urban forests account for a small but growing fraction of the state atmospheric CO_2 removals. Urban forests are included in the national GHG inventory (USEPA 2016) and feature in efforts to mitigate urban heat islands (USEPA 2017).

Soils

Soils in forests and other lands constitute significant carbon reservoirs participating in fluxes of CO_2, CH_4 and N_2O and are reported in the national GHG inventory (USEPA 2016). Soil carbon is one of many attributes monitored and mapped in the national gridded soil survey geographic database (gSSURGO, USDA 2016). Soil carbon stores are affected by vegetation growth and decay, weather and climate, disturbance, nutrient inputs, and microbial processes. Forest soils contain large stores of carbon accrued from the decay and incorporation of dead organic matter. Tillage, fertilization and irrigation affect soil carbon dynamics and GHG flux on croplands (De Gryze et al. 2008, Culman et al. 2014). Anoxic conditions found in wetland soils lead to accumulations of organic matter in sediments and to (de)nitrification and methanogenesis (IPCC 2006, 2014), and soils are an important carbon pool in

urban green spaces (Jo and McPherson 1995, Pouyat et al. 2006). ARB is working to include soils in the inventory for all IPCC land categories.

Advances in Methods

The approach to land carbon quantification described in the Methodology combines temporal geospatial data (LANDFIRE products) with ground-based tabular data. Airborne or space-based active sensor technologies such as Light Detection and Ranging (LiDAR) and Synthetic Aperture Radar (SAR) provide information on the three-dimensional structure of forests and other vegetation, and have been used in combination with ground-based data to generate high fidelity geospatially explicit estimates of above-ground biomass over large areas (Chen et al. 2012, Gonzalez et al. 2010, Zhang et al. 2014). Other efforts to interpret processes linking land carbon, disturbance and climate integrate remotely-sensed and ground-based data with process models (Liu et al. 2011, 2008; Nemani et al. 2002, Potter et al. 1993). Advances in remote sensing and analysis tools are rapid and will afford for future improvements in ARB land carbon quantification and monitoring at varieties of spatial and temporal scales.

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