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**Research article**

**An integrated approach to modeling changes in land use, land cover, and disturbance and their impact on ecosystem carbon dynamics: a case study in the Sierra Nevada Mountains of California**

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**Supplementary**

**1. Model description**

*IBIS ecosystem model*

IBIS focuses on plant functional types and is typically used for regional-scale assessment. Some controlling factors for forest systems are not considered in IBIS, such as tree species, age class and stem density. For IBIS, an automatic calibration procedure against a large observation dataset is developed as a post-processing step. Observations from remote sensing products are aggregated at county level. For example, the 1-km MODIS NPP of 2001–2005 are averaged at the county level and compared with IBIS NPP outputs to calculate the county-level differences and the related adjustment scalars. The scalars are assumed to help deal with unknown environmental factors. For the algorithm, the scalars for each county will be used to modify the forest Vmax parameter (Maximum Rubisco-limited rate of carboxylation) in a new IBIS run. On the other hand, forest biomass inventory data and crop grain yield statistics data are also summarized at county level in order for IBIS to compare with. The forest growth curves published by USDA Forest Service, the Carbon

OnLine Estimator (COLE, <http://www.ncasi2.org/COLE/>) database, are the general forest growth references to be compared with IBIS growth curves. An indicator of growth rate, e.g. total biomass carbon increase from 1 to 100 years, can be calculated from IBIS biomass pool. Comparing the pool value with the COLE 100 year growth value for the same geolocations, a scalar can be generated to increase or decrease IBIS biomass pool in a renewed simulation. Iterate 3~4 times, a stable carbon scalar can be obtained.

## 2. State class descriptions

*Table of state class descriptions*

**Table S1. State classes and their descriptions used within the LUCAS state and transition simulation model.**

LULC State Class	Description
Water	Water includes estuaries and bays, canals/aqueducts, lakes, reservoirs, rivers and streams. Cells are classified as water if vegetation and/or soils make up less than 25% of the area.
Developed	Development includes residential, industrial, commercial, transportation, and areas such as parks or other open spaces surrounded or otherwise dominated by an urban landscape.
Barren	Areas characterized by bare rock, gravel, sand, silt, clay, or other earthen material, with little or no “green” vegetation present regardless of its inherent ability to support life. Vegetation, if present, is more widely spaced and scrubby than that in the “green” vegetated categories; lichen cover may be extensive.
Forest	Forests are distinguished from other vegetated surfaces based on having a tree-crown areal density greater than 20%. This classification requirement represents the biophysical state of forest <i>cover</i> irrespective of land use. However, within the forest class we also include areas of recent harvest and natural disturbance (as opposed to modeling disturbance areas as separate state classes), where tree cover may not meet this threshold, resulting in a state class more consistent with forest <i>use</i> as opposed to cover. Because the model also tracks the age of each simulation cell, and thus the age of each forested cell, we can resolve the differences between forest <i>cover</i> and <i>use</i> through the examination of forest age structure.
Agriculture	Agricultural lands are characterized as any area used for the production of food and fiber, including cultivated cropland, pasture, orchards and vineyards, nurseries and ornamental horticulture areas, and confined livestock feeding operations.
Grassland	Areas dominated by herbaceous vegetation, generally greater than 80% of total vegetation. These areas are not subject to intensive management such as tilling, but can be utilized for grazing.
Shrubland	Areas dominated by shrubs; shrub canopy accounts for 25–100% of the cover.

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	Shrub cover is generally greater than 25% when tree cover is less than 25%.
	Shrub cover may be less than 25% in cases when the cover of other life forms (e.g. herbaceous or tree) is less than 25% and shrubs cover exceeds the cover of the other life forms.
Wetlands	Wetlands are those areas where the water table is at, near, or above the land surface for a significant part of most years.
Perennial Ice/Snow	All areas characterized by year-long cover of ice and/or snow.

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### 3. Land change projections

#### 3.1. Transition probabilities

For natural disturbance, we calculated the annual probability of wildfire in California for forest, grassland, and shrubland state classes using data from the Monitoring Trends in Burn Severity database [1]. The MTBS time series data provided annual areas of fire across major life-forms from 1984–2013. These data were used to calculate annual probabilities based on the following equation:

$$Bp = \left( \frac{Ba^{LF1\dots n}}{LFa^{1\dots n}} \right) \quad (1)$$

where  $Bp$  is the annual burn probability,  $Ba$  is the observed burn area by life-form (forest, grassland, shrubland), and  $LFa$  is the area of life-form  $n$  based on the initial conditions raster. We then calculated a distribution from the annual time series and applied the mean and standard deviation as input to the STSM.

Changes in, and between land-cover classes are defined here as a shift from one cover type to another, not caused or instigated by direct anthropogenic activities. For example, a land-cover change, defined here as “vegetation change” (see Table 2), could be the result of changes in precipitation resulting in woody encroachment on grasslands. Unlike the wildfire transition, there is very little in the way of data quantifying the rate of change between major vegetation classes due to natural shifts in range and suitability. Lacking any quantified rates of vegetation change we assumed an arbitrary annual transition probability of 0.01% for each of the natural vegetation transition pathways (i.e. changes between forest, grassland, and shrubland) in the A1B scenario.

#### 3.2. Transition targets

To project changes in land use and land cover consistent with the IPCC’s Special Report on Emission Scenarios (SRES) we used the downscaled scenarios developed by Sleeter et al. for the A1B scenario [2]. These scenarios were developed using a scenario downscaling model to regionalize projections of land use for the U.S. based on projections from an Integrated Assessment Model. The projections were specified at 5-year time-steps from 2000–2100. The A1B scenario is characterized by rapid economic growth and technological innovation in an increasingly globalized world. In the U.S., Sleeter et al. project rapid urbanization, expansion of agriculture to support an increase in demand for specialty crops and new generation biofuels, and high rates of forest harvest [2]. Cumulative areas of land-use change by category, as derived from this analysis, were used as transition targets within the STSM. Transition targets in ST-Sim force a deterministic amount of area to transition per timestep. The location of where these transitions take place is determined

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stochastically and weighted by the probability assigned to the transition for the state of a candidate cell [3].

#### 4. IBIS model initialization

For the current study, IBIS time dependent drivers are monthly precipitation and temperature and atmospheric CO<sub>2</sub> concentrations. Land cover change and fire disturbance are key drivers of IBIS, but they were excluded for the calibration scenario. For temperature and precipitation we used PRISM average historical climate for the years 1960–1990 for the calibration scenario and CGCM3 projections for future years (2001–2100) under the A1B scenario. Under the calibration scenario, CO<sub>2</sub> was fixed at 332 ppm (1960–1990 mean). For the A1B projection we used IPCC projections of CO<sub>2</sub> increase with a modified CO<sub>2</sub> fertilization effect described in Liu et al, 2011 [4].

##### 4.1. Living biomass

The 30m resolution vegetation canopy cover and canopy height data from the LandFire Project<sup>1</sup> were used to generate a 1-km resolution live biomass map based an empirical tree height-biomass lookup table and canopy cover fraction. For the CALIB scenario, this live biomass map was used in year 1, but was reset to 2% of the existing biomass at the end of year 10, imitating a stand-replacing logging event.

##### 4.2. Soil carbon

The SSURGO database was used to initialize IBIS soil C pools. The soil carbon calculation, before reaching an equilibrium state, is similar to Xia and others [5], which compares in-flux and e-flux of soil carbon to calculate the theoretical balance state for soils from 0–2 m deep. Because the modeled slow soil carbon pool in IBIS is almost linearly proportional to the NPP level, whereas the active and passive soil carbon pools are not, we only adjust the slow soil carbon pool size, deducting it from the total SSURGO soil carbon to calculate the passive soil carbon pool. In the model, a maximum amount of the passive soil carbon (reactive carbon, 10 kg C/m<sup>2</sup>) is allowed to participate in the soil decomposition process to help avoid excessive decomposition of passive soil carbon. Other intermediate carbon pools were arbitrarily set as a proportion of the living biomass pool. Output of IBIS soil carbon stock includes all internal (slow, fast, passive, active) pools. Therefore, LUCAS also represents the full set of soil carbon pools in its simulations.

#### 5. Forest age calculation

With a given forest biomass map, forest age can be derived based on growth curves and several scalars. The forest growth curve is a simple age (*A*) to biomass (*B*) lookup table (*T(B)*). For modeling consistency, we used the IBIS forest growth curve to estimate forest age, which was developed during model calibration. The IBIS growth curve could be higher or lower than the FIA growth curve due to

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<sup>1</sup> Data and information about the suite of data available from the LandFire project can be found on the World Wide Web at [landfire.cr.usgs.gov](http://landfire.cr.usgs.gov).

controlling input data and model parameters. The potential systematic discrepancy between the two curves can be described with a curve shift factor ( $F_s = 0\sim 1$ ). For example, if the IBIS growth curve is proportionally 30% lower than FIA growth curve,  $F_s$  will be given a value of 0.7. For IBIS, a reference forest pixel is assumed to be a forest stand with 70% canopy cover. On a given biomass map, the forest cover fraction ( $C_f$ ) can be varying from 0 to 100% on different land pixels. Therefore a cover factor ( $F_c$ ) was introduced to account for the influence of forest cover fraction. Forest age ( $A$ ) is then calculated as:

$$A = T(B) * F_c * F_s \quad (1)$$

$$F_c = \frac{0.7}{C_f} \quad (2)$$

Using this equation, if the observed forest-cover fraction ( $C_f$ ) is higher than the reference level (70%),  $F_c$  will be smaller than 1, therefore forest age will be lower than reference forest age. If the IBIS growth curve is systematically lower than the FIA growth curve ( $F_s < 1$ ), when a real biomass map is used as input,  $F_s$  will scale down the biomass level to get a younger forest age than using the FIA growth curve.

## 6. Carbon flux calculations

### 6.1. Automatic flows

#### Growth

The LUCAS model design incorporates a single annual NPP estimate, which reflects the production on mature forests only. For this reason it is necessary to develop a set of NPP scalars to reflect the reduced production at younger stands, so-as to avoid inflating the growth rate on young and regenerating stands. Using the IBIS CALIB scenario output, we calculated the NPP scalar as:

$$S_{AC1\ldots n}^{NPP} = \frac{\bar{x}_{AC1\ldots n}^{NPP}}{\bar{x}_{1850-1900}^{NPP}} \quad (3)$$

where  $S_{AC1\ldots n}^{NPP}$  is the NPP scalar for age classes 1 through  $n$ ,  $\bar{x}_{AC1\ldots n}^{NPP}$  is the average NPP estimate for age class 1 through  $n$ , and  $\bar{x}_{1850-1900}^{NPP}$  is the average NPP estimate for year 50–100 of the CALIB scenario. This period reflects an average mature NPP value for forests that are simulated as being between 40–90 years old under an average historical climate. The calculated NPP scalars are shown in Table 6.

Within LUCAS, the growth flow is calculated as a proportion of annual NPP (between 0–1, depending on forest age) which was defined above as a state attribute within the STSM. Therefore, at the cell level, growth is calculated as:

$$G_c = NPP * S_{AC1\ldots n}^{NPP} \quad (4)$$

where  $G_c$  is Growth,  $NPP$  is net primary production,  $S^{AC}$  is the age class coefficient for time  $t$  through  $n$  in Table 6. Total growth at the ecoregion level is the sum of growth across all cells classified as forest.

## 6.2. Litterfall

Litterfall was calculated for both living biomass and deadwood pools. In IBIS, litterfall is the annual fall of leaf and root biomass; woody biomass is moved first to a deadwood pool before being moved to the litter pool. Using the IBIS calibration scenario output, age-structured litterfall coefficients for living biomass were calculated to mimic this same flow of carbon in IBIS, as:

$$p(lf_{t1...n}^{LB}) = \frac{lf_t}{LB_{t-1}} \quad (5)$$

where  $p(lf^{LB})$  is the litterfall proportion at time  $t$  through  $n$ ,  $lf$  is the litterfall flux at time  $t$ , and  $LB$  is the living biomass stock density at time  $t-1$ . Age-based litterfall proportions were then averaged into 2, 5, and 10 year age-classes coefficients for use in the LUCAS SFM (Table 6). Within the SFM we use the age-structured coefficients to move proportions of the biomass pool into the litter pool annually, based on the age of the forest in a particular cell. Therefore, litterfall is:

$$lf_{LB} = LB * z_{ac_{1...n}}^{lf_{LB}} \quad (6)$$

where  $lf_{LB}$  is the litterfall flux,  $LB$  is the living biomass stock, and  $z_{ac_{1...n}}^{lf_{LB}}$  is the age structured litterfall (biomass) coefficient from Table 6. Similarly, the litterfall rate from the deadwood pool is determined by analyzing the IBIS output data and calculating the proportion of the deadwood pool which moves to litter annually as:

$$p(lf_{t1...n}^{DW}) = \frac{lf_t}{DW_{t-1}} \quad (7)$$

where  $p(lf^{DW})$  is the litterfall proportion at time  $t$  through  $n$ ,  $lf$  is the amount of litterfall in time  $t$ , and  $DW_{t-1}$  is the deadwood pool in time  $t-1$ . Annual IBIS-derived proportions are then averaged across 2, 5, and 10 year age classes (Table 6). In the LUCAS SFM, deadwood litterfall is then calculated as:

$$lf_{DW} = DW * z_{ac_{1...n}}^{lf_{DW}} \quad (8)$$

where  $lf_{DW}$  is the projected litterfall flux,  $DW$  is the deadwood stock, and  $z_{ac_{1...n}}^{lf_{DW}}$  is the age structured deadwood litterfall coefficient from Table 6. Therefore, total annual litterfall can be calculated as:

$$lf = lf^{DW} + lf^{LB} \quad (9)$$

## 6.3. Mortality

Because LUCAS simulated carbon change at the stand level, mortality is calculated as a proportion of the carbon stored in trees in a stand which die each year and are moved to the deadwood pool. IBIS output is used to determine the age-structured mortality rate as:

$$p(m_{t1...n}) = \frac{m_t}{LB_{t-1}} \quad (10)$$

where  $p(m_{t1...n})$  is the proportion of living biomass which dies and moves to the deadwood pool each year (not including mortality from disturbance and land use),  $m$  is the annual mortality flux in time  $t$  from IBIS, and  $LB$  is the living biomass stock in time  $t-1$ . Annual proportions are then averaged into age bins in Table 6. In the LUCAS SFM, annual mortality is then calculated as:

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$$m = LB * z_{AC_{1..n}}^m \quad (11)$$

where  $m$  is the projected mortality flux,  $LB$  is the living biomass stock, and  $z_{AC_{1..n}}^m$  is the age structured mortality coefficient from Table 6.

#### 6.4. Humification

Humification is the flux of carbon from the litter pool to the soil pool through transformation of organic material. Using IBIS output, we calculated the proportion of the litter pool humified each year as:

$$p(h_{t1..n}) = \frac{h_t}{Lt_{t-1}} \quad (12)$$

where  $p(h_{t1..n})$  is the proportion of the litter pool humified each year,  $h$  is the amount of litter to soil flux in time  $t$ , and  $Lt$  is the size of the litter stock in time  $t-1$ . LUCAS then calculates annual humification as:

$$h = Lt * z_{AC_{1..n}}^{Lt} \quad (13)$$

where  $h$  is the humification rate,  $Lt$  is the litter stock, and  $z_{AC_{1..n}}^{Lt}$  is the age structured humification coefficient from Table 6.

#### 6.5. Emission

Heterotrophic emissions are simulated for the litter and soil pools. The decomposition of the litter pool to the atmosphere is calculated as:

$$e_L = L * z_{AC_{1..n}}^{e_L} \quad (14)$$

where  $e_L$  is the litter emission rate,  $L$  is the litter stock, and  $z_{AC_{1..n}}^{e_L}$  is the age structured emission coefficient from Table 6. The soil emission rate is calculated as:

$$e_S = S * z_{AC_{1..n}}^{e_S} \quad (15)$$

where  $e_S$  is the soil emission rate,  $S$  is the soil stock, and  $z_{AC_{1..n}}^{e_S}$  is the humification coefficient from Table 6. For carbon stored in the wood products pool we assume the following calculation:

$$e_{WP} = WP * z_{AC_{1..n}}^{e_{WP}} \quad (16)$$

where  $e_{WP}$  is the biomass mortality rate,  $WP$  is the wood products stock, and  $z_{AC_{1..n}}^{e_{WP}}$  is the emission coefficient from Table 6.

## 7. Event-based flows

### 7.1. Clear-cut harvest

When a clear-cut harvest occurs we assume there are three fluxes involved: the transfer of living biomass to the wood products pool, mortality of living biomass, and emission from living biomass to the atmosphere resulting from the burning of slash. The emission of carbon is calculated as:

$$e_{LB}^{Hv} = LB * y_{LB}^{e_{Hv}} \quad (17)$$

where  $e_{LB}^{Hv}$  is the biomass emission rate,  $LB$  is the living biomass stock, and  $y_{LB}^{e_{Hv}}$  is the emission coefficient from Table 7. The transfer of carbon to the deadwood pool is calculated as:

$$m^{Hv} = LB * y_{LB}^{m_{Hv}} \quad (18)$$

where  $m^{Hv}$  is the biomass mortality rate,  $LB$  is the living biomass stock, and  $y_{LB}^{m_{Hv}}$  is the mortality coefficient from Table 7. Carbon removed from the ecosystem and stored in wood products is calculated as:

$$wp^{Hv} = LB * y_{LB}^{wp_{Hv}} \quad (19)$$

where  $wp^{Hv}$  is the transfer of carbon to the wood products pool,  $LB$  is the living biomass stock, and  $y_{LB}^{wp_{Hv}}$  is the harvest coefficient from Table 7. Therefore, the total flux of carbon from living biomass resulting from harvest is the sum of emission, mortality, and transfer to wood products.

### 7.2. Urbanization and deforestation

A similar approach is used when urbanization, or a conversion from forest into agriculture takes place. We assume nearly all carbon stored in the living biomass pool is removed and either transferred to the wood products pool or to the atmosphere. For both conversions, 20% of the biomass carbon stock is fluxed to the atmosphere. For conversion into agriculture, we assume all biomass is removed (the remaining 80%), whereas with urbanization we assume 10% of the living biomass remains. The calculation for biomass emission for both urbanization and conversion into agriculture was:

$$e^{LUC} = LB * y_{LB}^{e_{LUC}} \quad (20)$$

where  $e^{LUC}$  is the biomass emission rate,  $LB$  is the living biomass stock, and  $y_{LB}^{e_{LUC}}$  is the emission coefficient from Table 7. The wood product removal rate was calculated as:

$$wp^{LUC} = LB * y_{LB}^{wp_{URB}} \quad (21)$$

where  $wp^{LUC}$  is the transfer of carbon from biomass to the wood products pool,  $LB$  is the living biomass stock, and  $y_{LB}^{wp_{URB}}$  is the harvest coefficient from Table 7 for urbanization. For conversion

into agriculture we use  $y_{LB}^{wpAg}$  in substitution.

### 7.3. Wildfire

When wildfire occurs within the STSM, several additional flows are invoked including emission from biomass, litter, and soil, as well as a flux of carbon from biomass to the deadwood pool. Biomass emission is calculated as:

$$e_{LB}^{fire} = LB * y_{LB}^{e_{fire}} \quad (22)$$

where  $e_{LB}^{fire}$  is the biomass emission rate from wildfire,  $LB$  is the living biomass stock, and  $y_{LB}^{e_{fire}}$  is the coefficient from Table 7 for wildfire biomass emission. Litter emission from wildfire is calculated as:

$$e_{Lt}^{fire} = Lt * y_{Lt}^{e_{fire}} \quad (23)$$

where  $e_{Lt}^{fire}$  is the litter emission rate,  $Lt$  is the litter stock, and  $y_{Lt}^{e_{fire}}$  is the wildfire litter emission coefficient from Table 7. Soil emission was calculated as:

$$e_S^{fire} = S * y_S^{e_{fire}} \quad (24)$$

where  $e_S^{fire}$  is the soil emission rate,  $S$  is the soil stock, and  $y_S^{e_{fire}}$  is the wildfire soil emission coefficient from Table 7. Lastly, deadwood emission was:

$$e_{DW}^{fire} = DW * y_{DW}^{e_{fire}} \quad (25)$$

where  $e_{DW}^{fire}$  is the deadwood emission rate,  $DW$  is the deadwood stock, and  $y_{DW}^{e_{fire}}$  is the wildfire deadwood emission coefficient from Table 7. In addition to emission of carbon, we also transfer carbon from biomass to the deadwood pool as:

$$m_{LB}^{fire} = LB * y_{LB}^{m_{fire}} \quad (26)$$

where  $m_{LB}^{fire}$  is the living biomass mortality rate resulting from wildfire,  $LB$  is the living biomass stock, and  $y_{LB}^{m_{fire}}$  is the wildfire mortality coefficient from Table 6.

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