Carbon impacts of fire- and bark beetle-caused tree mortality across the western US using the community land model

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University of Idaho internal report

Date: February 25, 2015

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1. Introduction

Wildfires and bark beetle outbreaks cause major forest disturbances in the western US, affecting ecosystem productivity and thereby impacting forest carbon cycling and future climate. Despite the large spatial extent of tree mortality, quantifying carbon flux dynamics following fires and bark beetles over larger areas is challenging because of forest heterogeneity, varying disturbance severities, and field observation limitations. The objective of this study was to estimate these dynamics across the western US using the Community Land Model (version CLM4.5-BGC). This report details the progress, preliminary model results, and uncertainties of estimating regional carbon impacts of bark beetles and fire using the CLM4.5 model.

2. Background and model modifications

This work represents follow-up CLM modeling work that Dr. Steve Edburg (SE) had initiated. SE modified CLM3.5 to incorporate a bark beetle module that included a snagfall routine to represent the needle and standing dead trees on the landscape following outbreaks (Edburg et al. 2011). Our initial task was to continue the regional modeling work that SE had initiated in CLM3.5 on the Bluefire supercomputer. At the start of this project, NCAR upgraded from the Bluefire supercomputer to the Yellowstone supercomputer. During this transfer CLM3.5 was not installed on the new supercomputer and thus we upgraded the bark beetle subroutine of SE to a more recent version of CLM.

The bark beetle subroutine implemented in CLM3.5 (Edburg et al. 2011) was adapted to run in CLM4.5BGC. The bark beetle subroutine follows the harvest routine, but differs in that the bark beetle subroutine includes snag and dead foliage pools (for carbon and nitrogen) that have separate delayed and gradual transfer into the coarse woody debris and litter pool, respectively. CLM4.5BGC includes a slightly different soil subroutine with an expanded vertically resolved soil biogeochemistry routine and the bark beetle subroutine has been adapted to include the vertically resolved soil biogeochemistry (subroutine: clm_barkbeetle_v1.5, Appendix A).

For a single point run following a hypothetical bark beetle attack in (1995), foliage (Figure 1) and tree stem carbon (Figure 2) is transferred to dead foliage and snag pools. Note that Nitrogen pools follow the same delay periods and half-life decay as the Carbon pools, however for illustration we show only the Carbon pools. Following a one-year delay period, the dead foliage is transferred with an exponential decay function of 1-year half-life to the litter layer (Figure 1). Following a 5-year delay period (representing standing dead trees on the landscape), the snag Carbon is transferred with an exponential decay function of 10-years to the coarse woody debris pool (Figure 2).

Half-life constants in the clm_barkbeetle_v1.5 subroutine can be changed in the "CNDecompMod.F90" file of the CLM4.5BGC code (Appendix B). Half-life rate of the snag pools of the standard case in Edburg et al. (2011) was 10 years, the decay constant λ is 0.0693147, half-life rate of the dead foliage was 3 years and the decay constant λ is 0.231049, and the half-life rate of dead foliage implemented in the clm_barkbeetle_v1.5 bark beetle subroutine has been adapted to a more realistic rate (1 year and a decay constant λ *of* 0.693147) (Wulder et al. 2006).

3. Methods

CLM4.5-BGC is a land ecosystem model that mechanistically represents the exchanges of energy, water, carbon, and nitrogen with the atmosphere. The most recent iteration of the model has been expanded to include vertically resolved soil biogeochemistry and includes improved nitrogen cycle representations including nitrification and denitrification and biological fixation as well as improved canopy processes including photosynthesis. Prior to conducting simulations, we modified CLM4.5-BGC to include the effects of bark beetle-caused tree mortality on carbon and nitrogen stocks and fluxes (See section 2, Background and model modifications).

3.1 Model spinup

Because we found that the regular CLM model spinup had low amounts of Carbon over the western US, we corrected the carbon stocks (Figure 3). We reduced the background mortality from 2% to 1% and reduced the fire mortality fraction (by 75%) to increase the carbon stocks across the western US. Although the r^2 between CLM modeled carbon stocks and independent datasets derived from satellite observations (Blackard et al. 2008) and USFS FIA data only slightly improved, the total amount of carbon is much closer to the independent datasets (i.e., a reduced bias; Figures 4, 5, and 6). The model was spun up to 1980 and then control model runs and fire and bark beetle mortality are performed as the branch model runs with disturbance (Figure 3).

3.2 Fire and bark beetle-caused tree mortality datasets

We adapted the fire and bark beetle routines in the CLM model so that we could prescribe the area killed by fires and bark beetles. We conducted paired simulations (with and without) fire- and bark beetle-caused tree mortality by using regional data sets of observed mortality as inputs. Bark beetle-caused tree mortality was prescribed from a data set derived from US Forest Service aerial surveys from 1997 to 2010. Annual tree mortality area was produced from observed tree mortality caused by bark beetles, adjusted for underestimation (Meddens et al. 2012), and aggregated to the 0.5 degree grid used in the CLM model runs (Figure 7). In the simulations, we used the most realistic middle estimate of bark beetle mortality. Fires were prescribed using the Monitoring Trends in Burn Severity (MTBS) database from 1984 to 2010 (Figure 7). Annual tree mortality area was produced from forest cover maps and inclusion of moderate- and high-severity burned areas (Hicke et al. 2013). This dataset was aggregated to the 0.5 degree grid that was used in the CLM model runs (Figure 7).

3.3 Model outputs

After spinup, we ran the model three times. First, we ran the model without prescribed fire and bark beetle-caused tree mortality. Second, we ran the model with fire prescribed from 1984 to 2010. Third, we ran the model with prescribed bark beetle-caused tree mortality. Anomalies from the model runs without and with prescribed fire and bark beetle-caused tree mortality were calculated and the results were aggregated over the entire western US.

4. Results

Simulations show that reduction of vegetative carbon stocks caused by bark beetle-caused tree mortality was approximately 140 Tg C for the period 1997 to 2010, which is 2.9% of the total vegetative carbon across the western US (Figure 8). Reduction of vegetative carbon from fire-caused tree mortality was approximately 170 Tg C for the period 1997 to 2010, which is 3.6% of the total vegetative carbon across the western US (Figure 8). Fire-caused tree mortality in the period from 1997 to 2010 was almost identical to the amount lost from bark beetles (Figure 8).

Following reduction of live vegetative carbon stocks by fire and bark beetle disturbances, gross primary productivity declines (Figure 9). Reductions in GPP generally follow the mortality patterns of the years of severe mortality years. With the mortality autotrophic respiration decreases following both fire and bark beetle disturbances, as living trees that are killed do not respire anymore. Heterotrophic respiration is increased following bark beetle outbreaks as needles and fine woody debris from the killed trees are moved to the down woody debris and litter pools, while heterotrophic respiration following fires is decreased because the fine woody materials are burned up and follow a pulse of carbon into the atmosphere (not shown here) and only the large woody materials, which have much slower decomposition rates, are returned to the down woody debris pools.

Simulations show that maximum yearly reduction of net ecosystem productivity (NEP) caused by bark beetle-caused tree mortality is approximately -2 Tg C for the western US. Fires have greater reductions (-3 Tg/year) as well as greater increases in NEP (+1.5 Tg/year) and the temporal pattern is different. The reductions in NEP from bark beetles show a more constant reduction in NEP, while NEP following fire results in a more variable effect.

5. Discussion and conclusions

Our simulations showed that bark beetle and fire-caused tree mortality impacted approximately 3% of the carbon in trees across the western US from 1997 to 2010. Bark beetles and fire showed a similar magnitude of killed carbon for this period. Our simulated Carbon loss estimates were within the estimates from a study using spatial explicit datasets of Carbon stocks derived from remotely sensed and field data (Hicke et al. 2013).

Our simulations of net ecosystem productivity (nep) were of an order of magnitude lower then reported simulated by Kurz et al. (2008). Kurz et al. (2008) modeled the Carbon flux impacts of the mountain pine beetle outbreak across British Columbia using the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) and although the locations are different the outbreak area and resulting forest mortality is relatively similar (Meddens et al. 2012). Our results indicate that the Carbon dynamics of forests across the western US is more resilient then previously reported and matches with recent studies that find only very small impacts on bark beetles on carbon cycling (Brown et al. 2012; Moore et al. 2013).

There are several uncertainties in our simulations. First, although the Carbons stocks of the CLM spinup did show an improved match with two independent datasets after we reduced the fire and background mortality factors, there was still a poor spatial correspondence of Carbon stocks across the western US. Second, the CLM model was written for global modeling of energy fluxes and application of this model on a more regional scale might not capture the correct dynamics of forest ecology. Third the driver datasets of bark beetles and fires have limitations and the modeled impacts are only as accurate as these datasets are.

Further research could include (a) modeling impacts of fire and bark beetles on future Carbon stocks and fluxes, (b) improvement of total Carbon stocks across the western US, and (c) perform sensitivity studies on how location, climate, disturbance severity, soil characteristics, and snag fall rates, influence the dynamics of the Carbon fluxes following large fires and insects outbreaks.

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Wulder, M.A., Dymond, C.C., White, J.C., Leckie, D.G., & Carroll, A.L. (2006). Surveying mountain pine beetle damage of forests: A review of remote sensing opportunities. *Forest Ecology and Management, 221*, 27-41

Figures

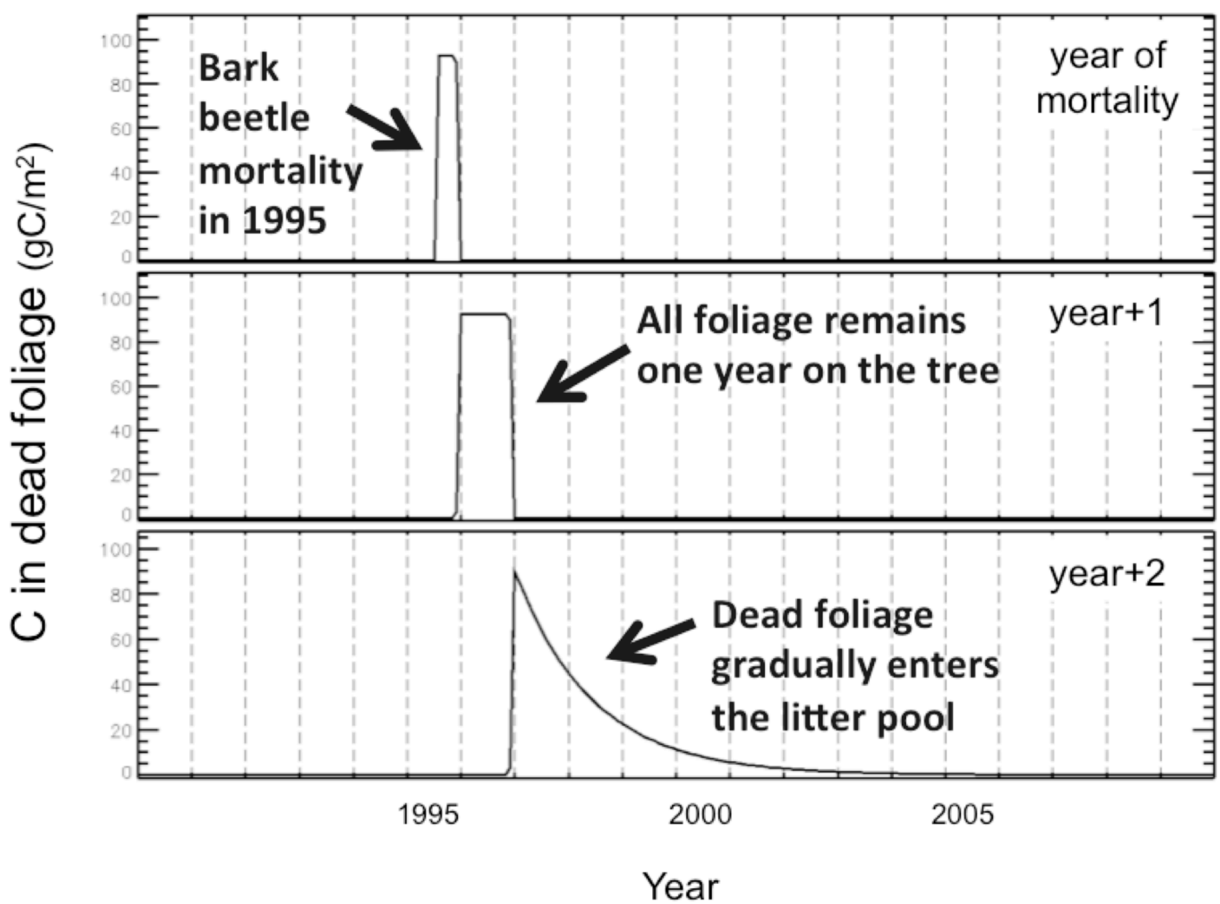

Figure 1. Dead foliage pools at (top) year of bark beetle attack, (middle) one year following attack, and (bottom) two years following attack from a point model run in central Idaho. The foliage carbon pools (from current year to 2-year following) represent the amount of needles on the dead trees in the ecosystem following beetle attack before a proportion of the needles start to fall to the forest floor and become part of the litter carbon pool.

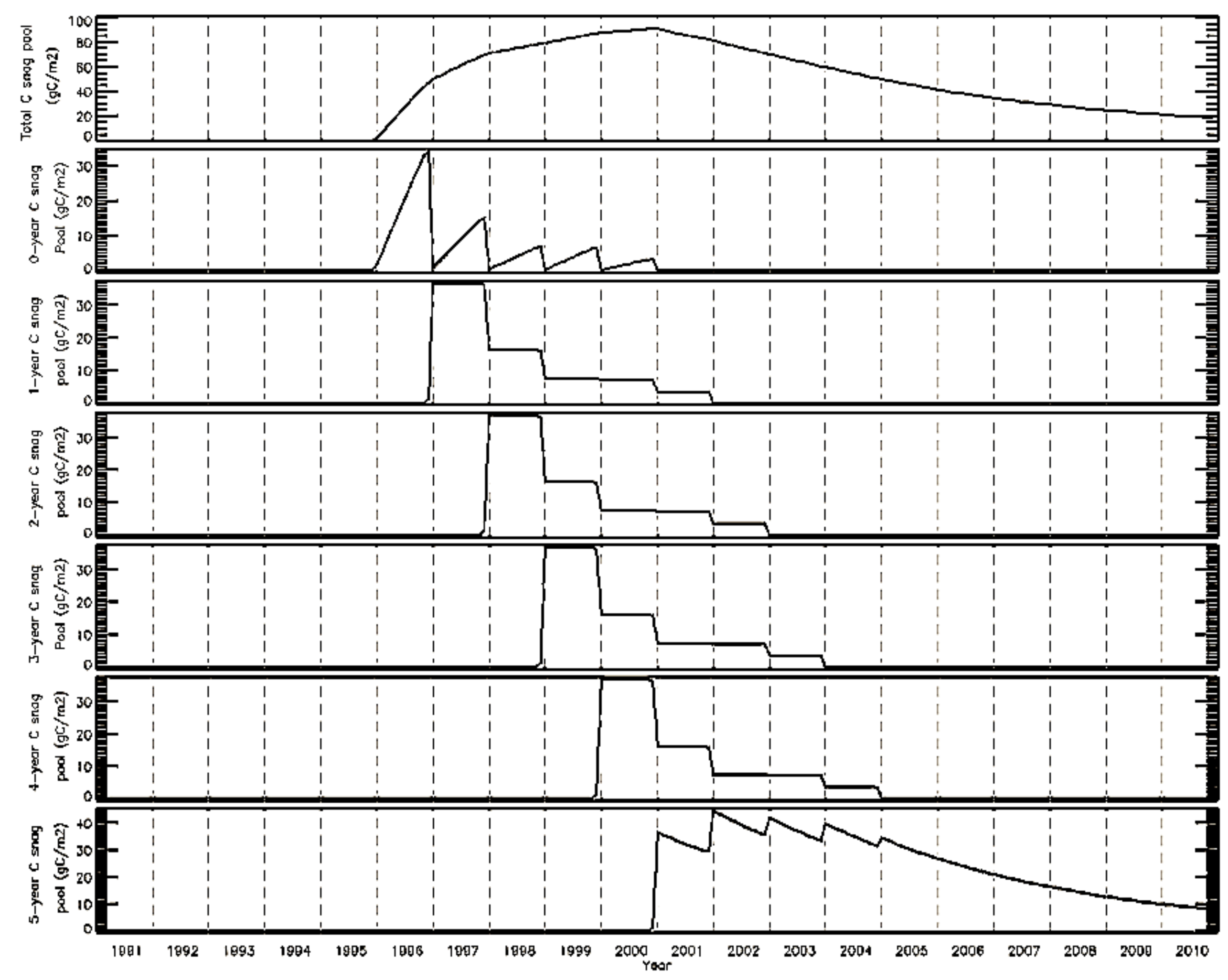

Figure 2. Total snag carbon pool (top) and snag delay carbon pools (from current year to 5-year) representing standing dead snags in the ecosystem following beetle attack before a proportion of the snags start to fall to the forest floor and become part of the coarse woody debris pool.

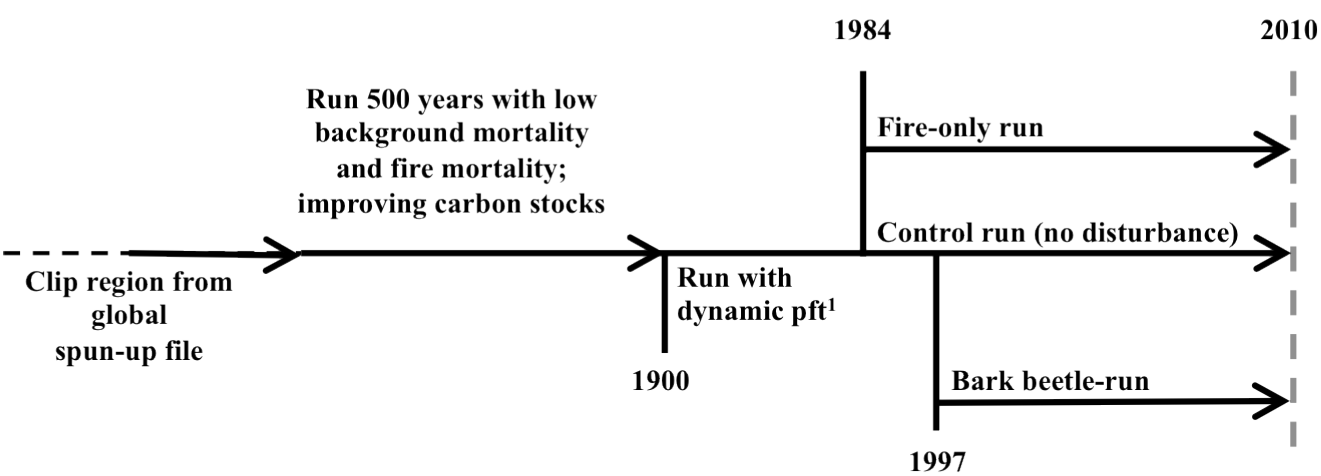

Figure 3. CLM spin up scheme and branch model runs with bark beetle and forest fire disturbances.

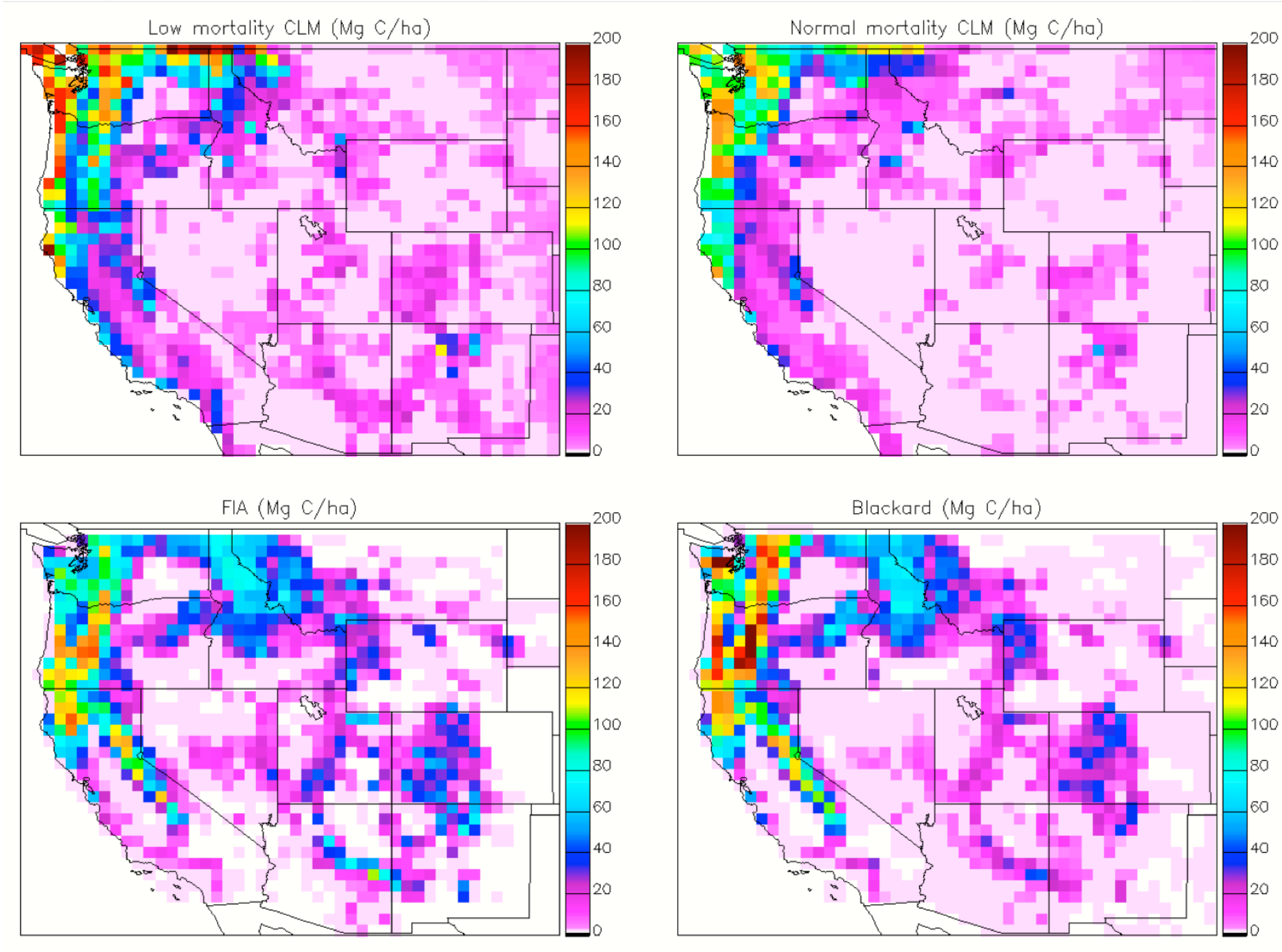

Figure 4. Comparison of (top left) CLM corrected by adjusting the background mortality and fire mortality fraction, with (top right) normal CLM spinup without adjustments, (bottom left) carbon stocks derived from USFS FIA, data and (bottom right) a dataset derived from Blackard et al (2008). The corrected carbon stocks (top right) improve the match between the amounts of carbon on the landscape across the western US as compared to the FIA and Blackard et al (2008) datasets.

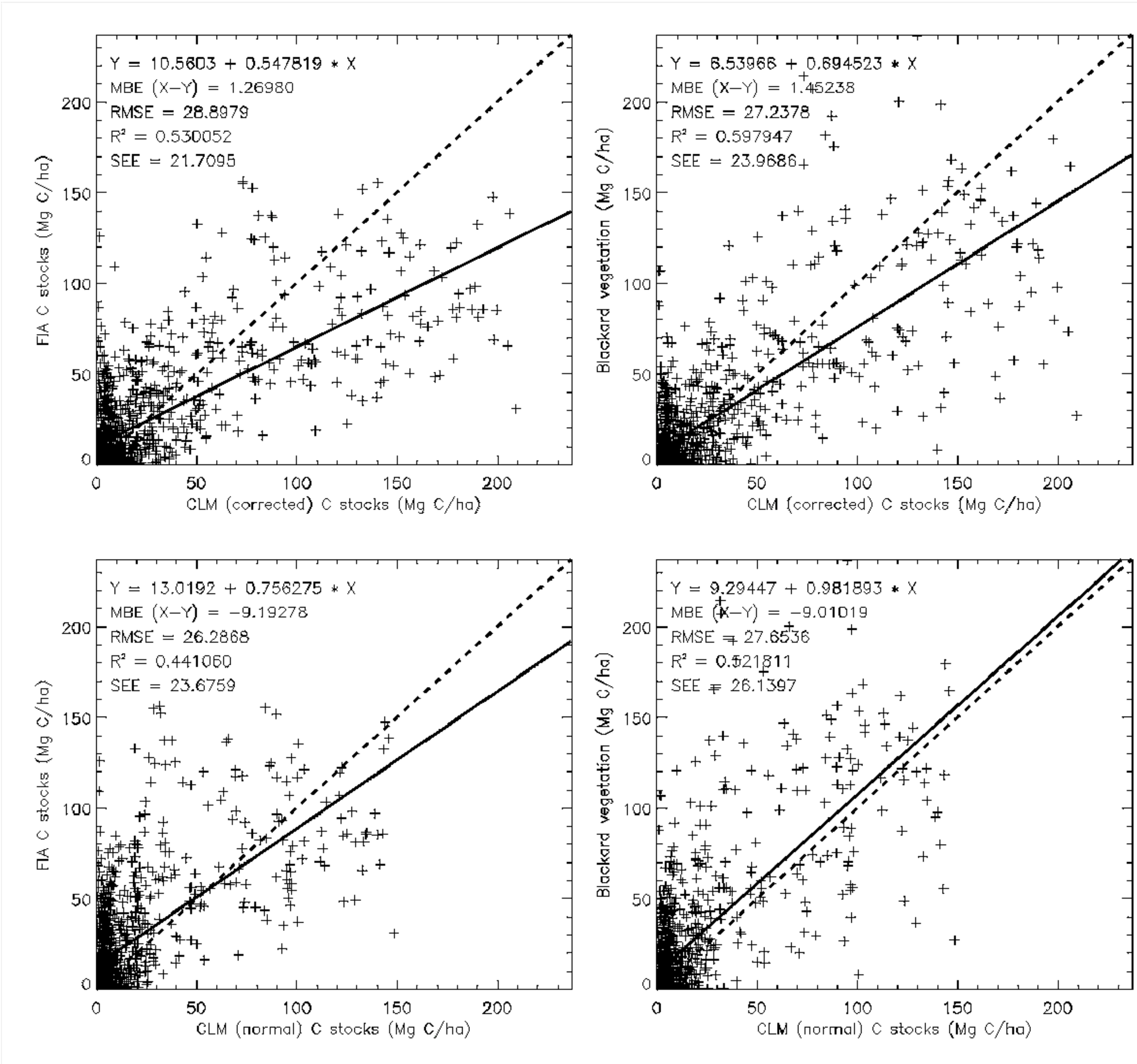

Figure 5. Comparison of CLM corrected (by adjusting the background mortality, top) carbon stocks and CLM normal spin up (bottom) carbon stocks across the western US. Independent datasets are Blackard et al (2008) and a dataset derived from USFS FIA data.

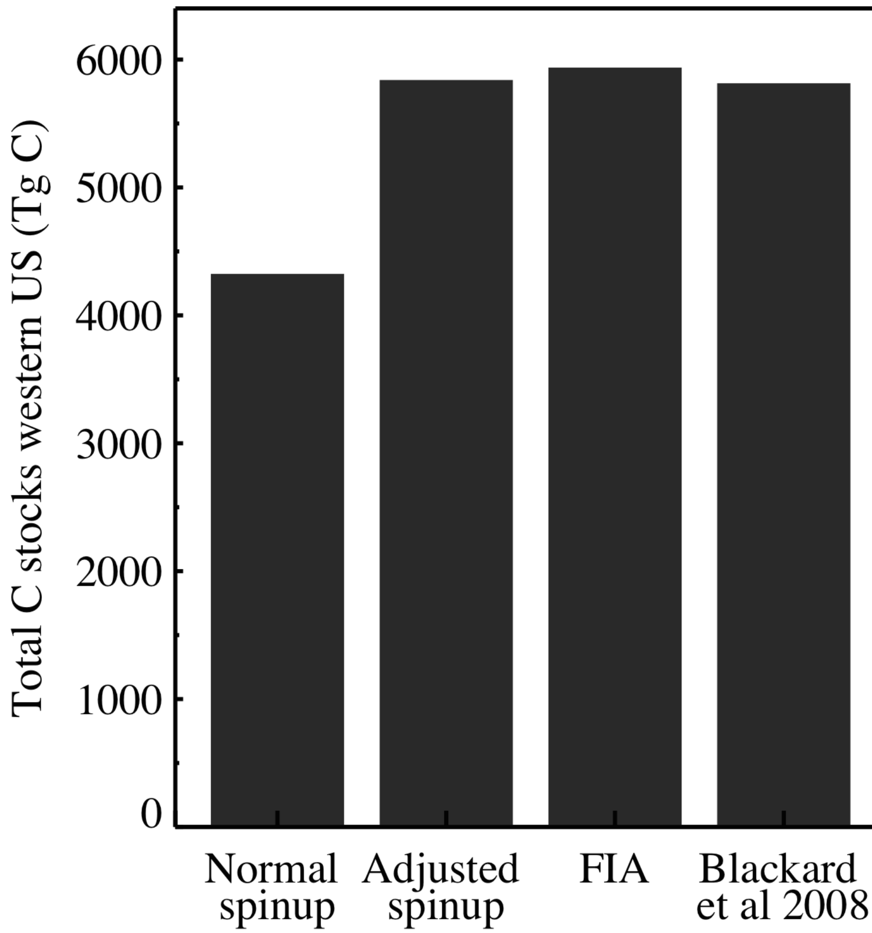

Figure 6. Total carbon stocks across the western US, showing the improved total amount of carbon when reducing the background mortality (from 2% to 1%) and reducing fire mortality (with 75%) (adjusted spinup) as compared to a regular CLM spinup (normal spinup) and two independent datasets (Forest Inventory Analysis and Blackard et al. 2008). Note that the spatial correlation slightly improve, indicating spatial differences of carbon amounts across the western US (refer to figure 4 and 5).

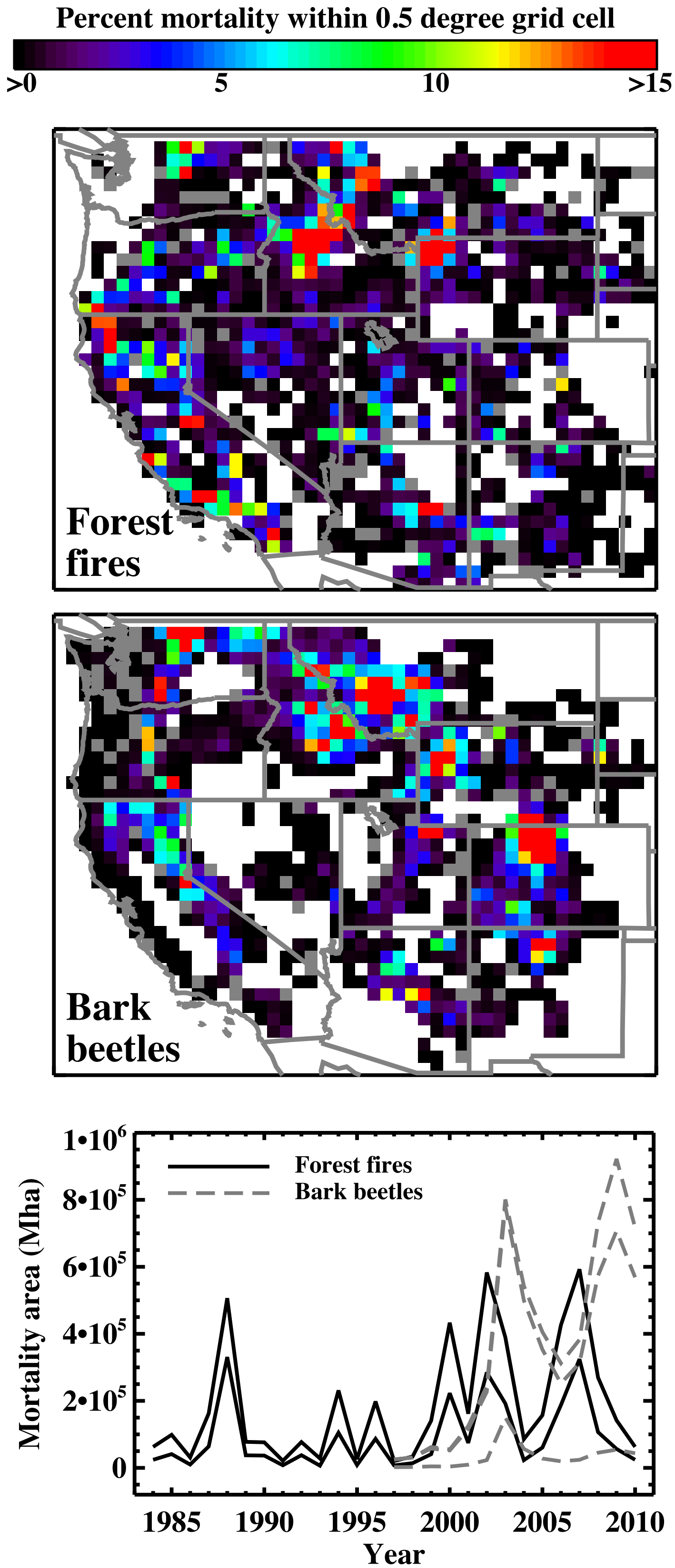

Figure 7. MTBS forest fires and bark beetle caused tree mortality (in area per grid cell) datasets formatted to the 0.5 degrees CLM grid over the western US to prescribe fire and beetle disturbances in the CLM model runs.

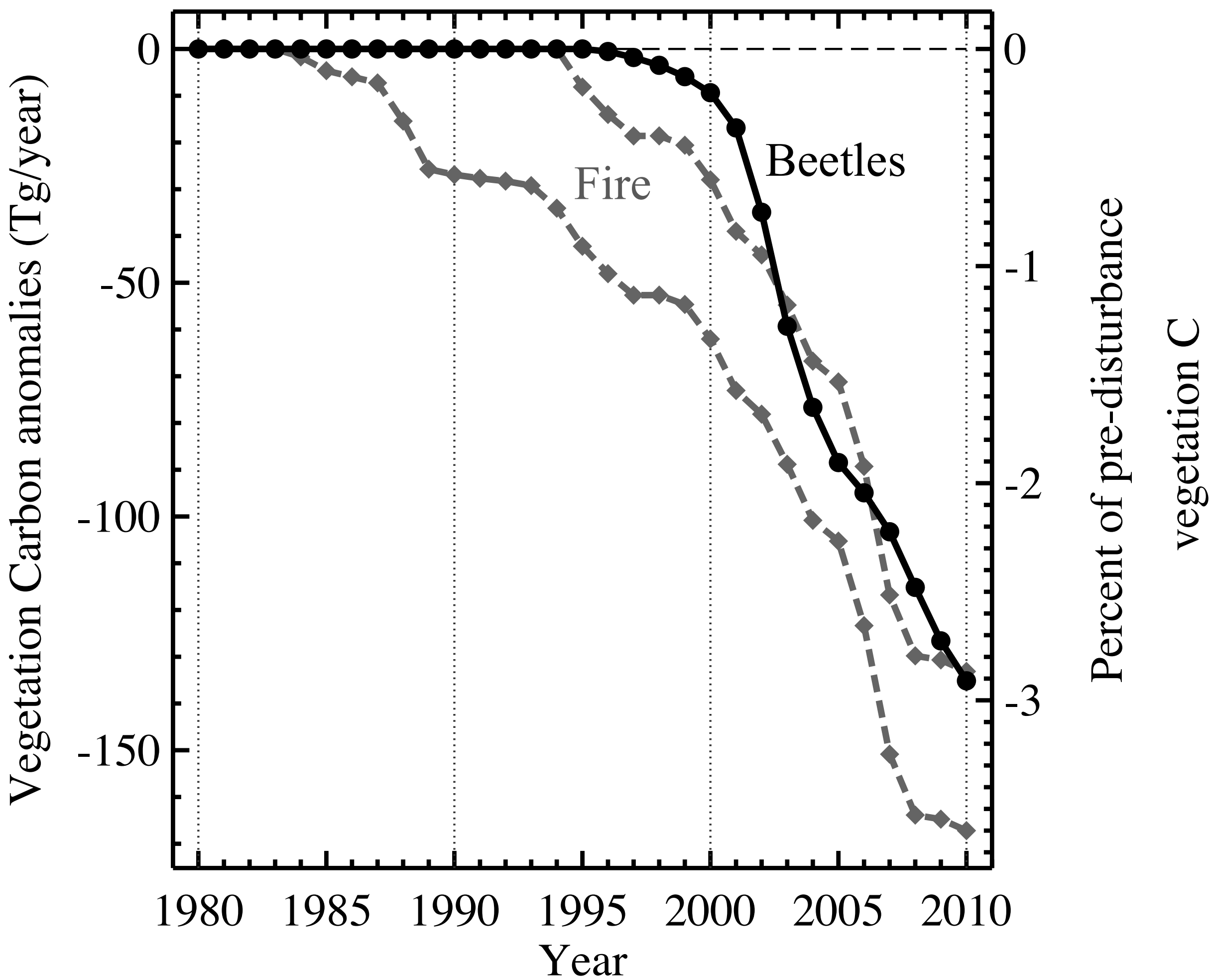

Figure 8. Reductions of vegetation Carbon stocks (Tg/year) caused by fire (from 1984 – 2010 and from 1997 – 2010) and bark beetles (from 1997 – 2010) across the western US. Reductions are calculated as anomalies (and as a percentage of all affected pixels) from a model run without prescribed fire and bark beetle disturbances.

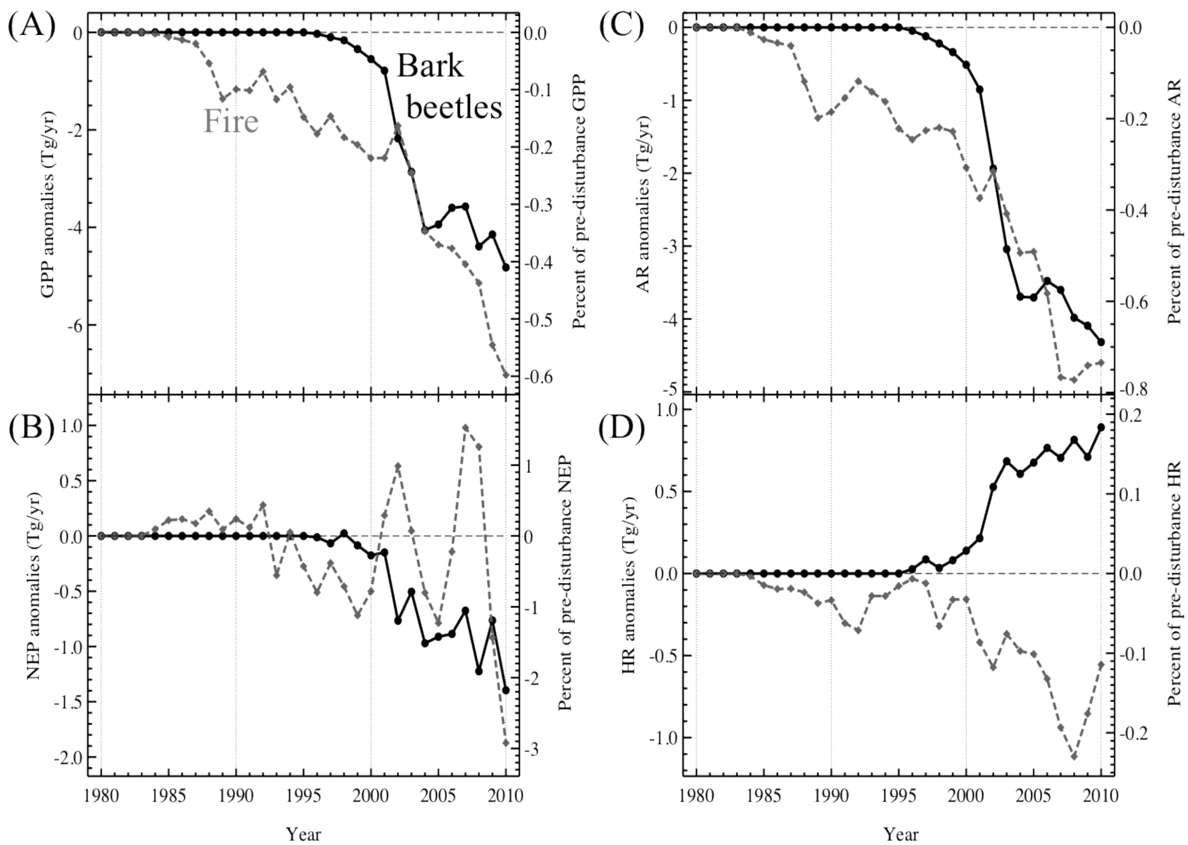

Figure 9. Modeled (A) gross primary productivity (GPP, Tg/year), (B) net ecosystem productivity (NEP, Tg/year), (C) autotrophic respiration (AR, Tg/year), and (D) heterotrophic respiration (HR, Tg/year) dynamics following fire and bark beetle-caused tree mortality for the entire western US. Calculated as anomalies from a model run without prescribed fire and bark beetle disturbances.

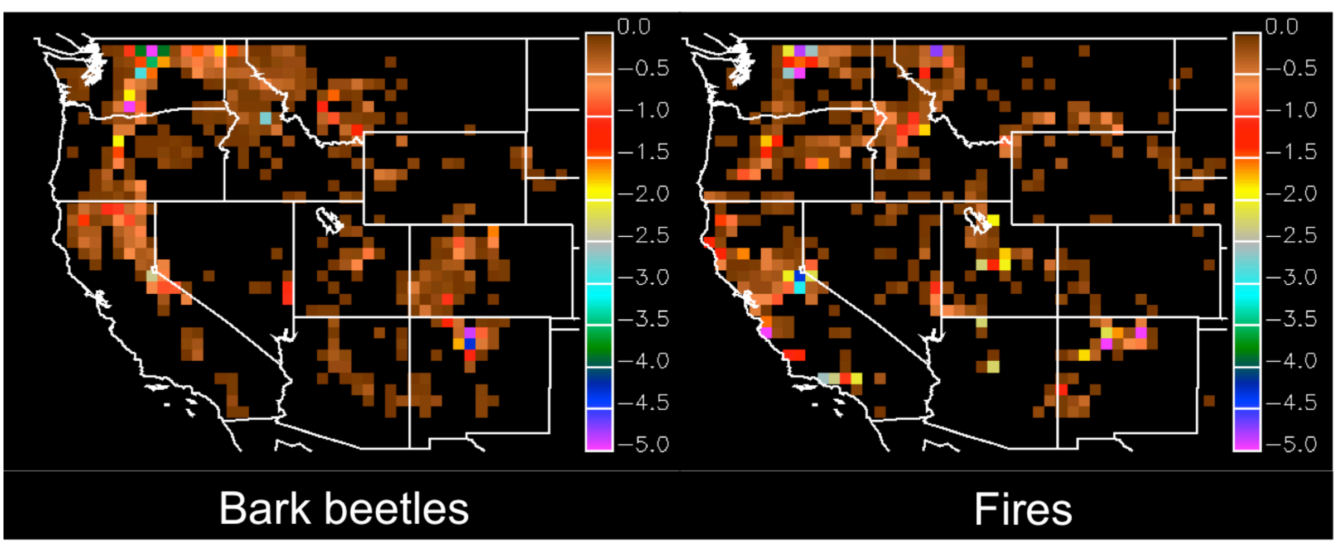

Figure 10. Reductions of vegetative Carbon stocks following bark beetle and fire-caused tree mortality (in Tg C) across the western US.

Appendices

Appendix A. Description of CLM bark beetle subroutine implemented into CLM4.5BGC (clm_barkbeetle_v1.5)

Readme file of clm_barkbeetle_v1.5:

```
;-----------------------------------------------------------------
; AMeddens – University of Idaho – 27 Nov 2013
;-----------------------------------------------------------------
; Content: Version V1.5 of the Bark beetle / MTBS fire code
;-----------------------------------------------------------------
;  Notes:
;   - Routine was implemented in trunk/branch/tag CLM4_5_8 (CLM4.5BGC version 8)
;   - All entries are indicated by:  "! - AMeddens - Added bark beetle routine (22/07/2013)"
;   - The V1.5 code has many print outs still incorporated for debugging (i.e., "write(iulog,*) '….' ")
;   - Some features are hard coded and could be made dynamic by modifications to the
;        input parameters
;-----------------------------------------------------------------
 (1) CODE modifications summary

clmtype.F90                         <> Minor mods (initialization of bb variables)
clmtypeInitMod.F90                  <> Minor mods (initialization of bb variables)
CNBalanceCheckMod.F90               <> Minor mods (balance check)
CNCIsoFluxMod.F90                   <> Minor mods
CNCStateUpdate1Mod.F90              <> C-flux updates
CNCStateUpdate2Mod.F90              <> Main C-flux updates
CNDecompMod.F90                     <> Snag pool to CWD half-live constants
CNEcosystemDynMod.F90               <> Minor mods
CNFireMod.F90                       <> Re-route read in MTBS fire data (farea_burned)
CNGapMortalityMod.F90               <> Gap mortality adjusted for West US (from 2% to 1%)
CNiniTimeVar.F90                    <> Minor mods
CNNStateUpdate1Mod.F90              <> N-flux updates
CNNStateUpdate2Mod.F90              <> Main N-flux updates
CNPrecisionControlMod.F90           <> Minor mods
CNrestMod.F90                       <> Minor mods
CNSetValueMod.F90                   <> Minor mods
CNSummaryMod.F90                    <> Minor mods
CNWoodProductsMod.F90               <> Minor mods
histFldsMod.F90                     <> Minor mods
pftdynMod.F90                       <> Read in of BB/FIRE datasets + separate beetle routine +
                                           calculation of annual mortality (am) rate and bark beetle
                                           pools and fluxes
;---------------------------------------
(2) CLM and disturbance datasets grid/pft/beetle grids/ fire grids
   /1_Fire_Beetle_Cstocks_data/1_Carbon_Stocks/  → Blackard and FIA Carbon stocks datasets
   /1_Fire_Beetle_Cstocks_data/2_Bark_beetles/   → Low, Mid, High mortality estimates from aerial
                                                      surveys (Meddens et al. 2012) aggregated
                                                      to 0.5 degree gridcell
```

/1_Fire_Beetle_Cstocks_data/3_Fire/ → High and Mod + High severity fires from MTBS (Hicke et al 2013) aggregated to 0.5 degree gridcell

/2_CLM_data/ → CLM data needed for running CLM4.5BGC

;---------------------------------------

(3) IDL code for updating modifying NETCDF files to read in Prescribed Fire/Beetle data

idl1_add_bb_pftdyn_wus.pro
idl2_modify_mf_fire.pro

surfdata.pftdyn_0.5x0.5_westernUS_rcp8.5_simyr1850-2100_c130529.nc
surfdata.pftdyn_0.5x0.5_westernUS_rcp8.5_simyr1850-2100_c130529_bb0_fire2.nc
surfdata.pftdyn_0.5x0.5_westernUS_rcp8.5_simyr1850-2100_c130529_bb2_fire0.nc

;---

(4) Spinup files for the 0.5 western US
clm45bgc_05deg4508_hist_westUS
clm45bgc_05deg4508_spin_westUS

;---

Examples:

Code in [CNDecompMod.F90] that calculates snagfall and foliage transfer rates:

```
!Calculate snag fall decomp rates
 k_ls3 = 0.693147_r8 !-  1-year half life is: ln(2)/1  = 0.693147_r8
 k_s6 = 0.0693147_r8 !- 10-year half life is: ln(2)/10 = 0.0693147_r8
 !- Note snag6c_to_decomp_cpool is C/sec
 !-
 !- From % per year to % per sec: 1/3149600
 !- Old values from S.EDBURG: k_ls3 = 0.0625_r8
 !- Old values from S.EDBURG: k_s6  = 0.015625_r8  !- 1/0.015625_r8 = 64 <> 64-year half-live??!?

 !- SNAG half-live leaking to CWD - FLUX - And transfer from m2 to m3,
 !   Note: When adding to decomp_cpool (*1/0.0175128179162552)!!!
 snag6c_to_decomp_cpool(c)          = snag6c(c) * k_s6 / 31536000_r8   !7884000._r8
 leafsnag3c_to_decomp_litrmet(c)    = leafsnag3c(c) * 0._r8    * ( k_ls3 / 31536000_r8)   !7884000._r8)
 leafsnag3c_to_decomp_litrcel(c)    = leafsnag3c(c) * 0.76_r8 * ( k_ls3 / 31536000_r8)   !7884000._r8)
 leafsnag3c_to_decomp_litrlig(c)    = leafsnag3c(c) * 0.24_r8 * ( k_ls3 / 31536000_r8)   !7884000._r8)

 snag6n_to_decomp_npool(c)          = snag6n(c) * k_s6 / 31536000_r8   !7884000._r8
 leafsnag3n_to_decomp_litrmet(c)    = leafsnag3n(c) * 0._r8    * ( k_ls3 / 31536000_r8)   !7884000._r8)
 leafsnag3n_to_decomp_litrcel(c)    = leafsnag3n(c) * 0.76_r8 * ( k_ls3 / 31536000_r8)   !7884000._r8)
 leafsnag3n_to_decomp_litrlig(c)    = leafsnag3n(c) * 0.24_r8 * ( k_ls3 / 31536000_r8)   !7884000._r8)

write(iulog,*) '------------------------------------'
write(iulog,*) 'CNDecomp:: DECAY FUNCTION'
write(iulog,*) 'CNDecomp:: year,mon,day,sec,c,',year,mon,day,sec,c
write(iulog,*) '------------------------------------'
write(iulog,*) 'decay const. snag (k_s6)' , k_s6
write(iulog,*) 'CNDecomp:: c, snag6c',c,snag6c(c)
write(iulog,*) 'snag6c_to_decomp_cpool(c)', snag6c_to_decomp_cpool(c)
write(iulog,*) '- - - - - - - - -'
write(iulog,*) 'decay const. dead foliage (k_ls3)' , k_ls3
write(iulog,*) 'CNDecomp:: c, leafsnag3c',c,leafsnag3c(c)
write(iulog,*) 'snag3c_to_decomp_litrcel(c)', leafsnag3c_to_decomp_litrcel(c)
write(iulog,*) 'snag3_to_decomp_litrlig(c)', leafsnag3c_to_decomp_litrlig(c)
write(iulog,*) '------------------------------------'
```

Code in [pftdynMod.F90] that reads Bark beetle grid from:
surfdata.pftdyn_0.5x0.5_westernUS_rcp8.5_simyr1850-2100_c130529_bb2_fire0.nc

```
!- Bark_beetles
allocate(arrayl(begg:endg))

call ncd_io(ncid=ncid, varname= 'BARK_BEETLE', flag='read', data=arrayl, dim1name=grlnd, &
     nt=ntime, readvar=readvar)
if (.not. readvar) call endrun( trim(subname)//' ERROR: BARK_BEETLE not on pftdyn file' )
barkbeetle(begg:endg) = arrayl(begg:endg)

deallocate(arrayl)
```

Code in [pftdynMod.F90] that reads calculates the bark beetle mortality at each time step:

```
   if (do_barkbeetle) then
      call get_curr_date(year,mon,day,sec)
      nstep = get_nstep()
      if(mon == 08 .and. day == 01 .and. sec == 0) then
         am = barkbeetle(g)                 !- Percent forest mortality per year
         m  = am / dt                       !- BB mortality per sec.
         write(iulog,*)'--------------------------------------------------'
         write(iulog,*) 'pftdynMod.F90::It is AUG 1st Bark beetle mortality'
         write(iulog,*) 'pftdynMod.F90::Date:year,mon,day,sec', year,mon,day,sec
         write(iulog,*) 'pftdynMod.F90::Timestep  ', nstep
         write(iulog,*) 'pftdynMod.F90::am (annual mortality) ', am
         write(iulog,*) 'pftdynMod.F90::m (annual mortality/timestep(=1800 sec)) ', m
         write(iulog,*)'--------------------------------------------------'
      else     ! If not aug 1st
         m = 0._r8
      end if
   else         ! If do_barkbeetle = 0
      m = 0._r8
   end if

   ! pft-level barkbeetle carbon fluxes
   ! displayed pools
   bb_leafc_to_litter(p)         = leafc(p)            * 0._r8
   bb_leafc_to_leafsnag1c(p)     = leafc(p)            * m ! addition of leaves to leaf snagpool
   bb_frootc_to_litter(p)        = frootc(p)           * m
   bb_livestemc_to_litter(p)     = livestemc(p)        * m !- Note weird error found here

   bb_deadstemc_to_snag1c(p)     = deadstemc(p)        * m ! addition of deadstem to snagpool
   bb_deadstemc_to_prod10c(p)    = deadstemc(p)        * 0._r8
   bb_deadstemc_to_prod100c(p)   = deadstemc(p)        * 0._r8
```

Appendix B. Calculating the half live time of snags and dead foliage pools

Exponential decay function: $N(t) = N_0 e^{-\lambda t}$, with *N(t)* carbon pool at time *t* (in years) and with *ln(2)/λ* as the half life time ($t_{1/2}$ in years) of the carbon pools. The formula used in the model is then $\frac{dN}{dt} = -\lambda N$ with where *N* is the remaining carbon at a given time (year) and decay constant λ is ln(2)/$t_{1/2}$. (Note λ is also called k the decay constant sometimes).

Half-life rate of the snag pools of the standard case in Edburg et al. 2011 was 10 years, the decay constant λ is 0.0693147, half-life rate of the dead foliage was 3 years and the decay constant λ is 0.231049, and the half-life rate of the more realistic dead foliage is 1 year and the decay constant λ is 0.693147.