Supplementary Material

Balancing trade-offs between ecosystem services in Germany's forests under climate change.

Running head: Forest ecosystem services under climate change

Author names and affiliations

Martin Gutsch, Petra Lasch-Born, Chris Kollas, Felicitas Suckow, and Christopher P O Reyer

Potsdam Institute for Climate Impact Research (PIK)

Telegraphenberg A 31

14473 Potsdam

P.O. Box 60 12 03

14412 Potsdam

gutsch@pik-potsdam.de

lasch@pik-potsdam.de

reyer@pik-potsdam.de

kollas@pik-potsdam.de

suckow@pik-potsdam.de

Corresponding author: Martin Gutsch, +49 (0)331 2882632, gutsch@pik-potsdam.de

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Description of modelled Ecosystem service indicators with the model 4C

The process-based model 4C (FORESEE: forest ecosystems in a changing environment) is a forest dynamics model (Lasch *et al.,* 2005), developed at PIK to investigate long-term forest behaviour under changing environmental conditions (Bugmann *et al.,* 1997).

Running the model, it needs to be initialized by a forest stand description (dimensions of trees or seedlings) and information about the physical and chemical parameters of the soil profile and subsequently to be driven by weather data (temperature, precipitation, air vapour pressure, relative humidity, solar radiation and wind speed) at daily resolution. The model uses tree- and stand-level variables to simulate the composition of tree species, forest structure, as well as carbon and water balances of the ecosystem. The development of a forest stand is described by the reproduction, growth and mortality of tree cohorts, which are classes of trees with identical dimensions, foliage, sapwood, heartwood and fine root biomass, species type and age. Tree cohorts compete for light, water and nutrients available in the soil.

Tree cohorts compete for light by means of crown height and crown area, and for water and nutrients available in the soil. The latter competition is modelled via absorption of water and nitrogen by fine roots in proportion to the fine root mass of the individual cohorts in the soil layers. A multi-layered soil module is further needed in 4C to calculate the transport of heat and water, as well as the dynamics of nitrogen and carbon based on the decomposition and mineralisation of organic matter (Kartschall *et al.,* 1990; Grote *et al.,* 1998). The inherent processes of the model are described as follows:

Timber harvest (C_H)

Timber harvest was simulated at the end of each year. For this study we pre-defined percentages of stocking volume (see chapter 2.4. of the paper) which have to be removed from the stand. Hereby we chose cutting from above, which means that the target volume is achieved by selecting trees for harvesting from the stronger end of the diameter distribution. All harvested stem wood was summed up to the indicator timber harvest in tons of carbon per hectare and year by multiplying the 4C-output, given in tons of dry matter, by 0.5. When the pre-defined rotation time (Table 3 of the paper) was reached, the entire forest stand was harvested and planted with 2000 plants of the corresponding tree species (Table 2 of the paper).

Above and belowground biomass (C_{BM})

Biomass growth in 4C was modelled on a yearly time step by allocating the carbon gained by the net primary production (NPP) of a year to six biomass pools foliage, twigs and branches, sapwood, heartwood, coarse roots and fine roots. This allocation follows specific rules and is based on the framework of Mäkelä (1990):

(1) Carbon-balance: net growth is the difference between gross growth and the three factors senescence, growth respiration and maintenance respiration (and relations between these factors)
(2) Functional balance (Davidson ,1969), which states that the shoot-root ratios are adjusted so as to maintain a balanced carbon-nitrogen ratio in the plant.
(3) Pipe model theory (Shinozaki *et al.*, 1964), which reasons that each unit of foliage requires a unit pipeline of wood to conduct water from the roots (both the latter are seen as evolutionary adaptations)
(4) Principle of mass conservation
(5) A height growth strategy that maximises survival

Net ecosystem production (C_{NEP})

Net ecosystem production (NEP) is net primary production (NPP) minus soil respiration. The NPP was modelled in 4C analogue to the photosynthesis module described by Haxeltine and Prentice (1996) which is based on the mechanistic photosynthesis model of Farquhar *et al.* (1980) as simplified by Collatz *et al.* (1991). It describes net daily photosynthesis depending on absorbed photosynthetically active radiation. As this approach assumes abundant water and nutrient supply, the calculated NPP is further reduced by a drought related factor that is determined upon cohort-specific demand and supply. Soil respiration as the other component of the NEP is described under the ES Soil carbon.

Soil dynamics: Soil carbon (C_S), Nitrogen leaching (W_N) and Percolation (W_P)

The soil is divided into different layers with optional thickness following the horizons of the soil profile. Each layer, the humus layer and the deeper mineral layers, is regarded as homogeneous concerning its physical and chemical parameters. Water content, soil temperature, carbon and nitrogen turnover of each soil layer are estimated as functions of the soil parameters, air temperature, stand precipitation and deposition. The time step of the soil model is one day due to the high dynamics of the water processes.

Yearly production of foliage litter, dead branches and dead fine roots are added to the pool of soil organic matter. Carbon and nitrogen mineralisation of this soil organic matter is calculated dependent on soil water content, soil temperature, soil pH value and substrate-specific turnover rates (Franko, 1990; Kartschall *et al.*, 1990; Running and Gower, 1991). These processes are described as first order reactions for each layer and lead to the release of carbon, nitrogen and CO_2 (Goto *et al.*, 1994). The released products (1) are fed back to the pool of soil organic matter, (2) are absorbed by plant uptake (nitrogen), (3) are translocated to lower soil layers due to soil water dynamics (mineralized nitrogen→ nitrogen leaching) and (4) are released to the atmosphere (CO_2).

The soil water content and the resulting percolation were calculated by a simple bucket model approach. The input into the first layer is the net precipitation after canopy interception. For each other layer, the input is equal to the percolation water from the above layer. The output is estimated from the percolation water into the next layer, the soil evaporation (up to a certain depth), and the water uptake by roots. If the water content of a layer is greater than the field capacity the percolation water is calculated according to a special water conductivity parameter which depends on the soil texture (Glugla, 1969;Koitzsch, 1977). If air temperature is below freezing (0°C), the precipitation is stored as a water equivalent in a pool of snow, which is emptied as a function of temperature. The melt-water will then be added to the uppermost soil layer. In the case of frozen soil no percolation occurs.

Root uptake is limited by the transpiration demand of all trees of the cohort and the plant available water. It is assumed that optimal conditions for water uptake exist only when the water content does not vary by more than 10 percent from field capacity, otherwise there is a linear reduction of the plant available water (Chen, 1993). The water uptake of each cohort is calculated based on the cohort's relative share of fine roots on the total amount of fine roots.

Deadwood (C_{DW})

In 4C the mortality of trees fills the deadwood pool. The mortality module of 4C consists of the following two kinds of mortality. The so called 'age related' mortality based on life span corresponds to the intrinsic mortality developed by Botkin (1993) and the response of trees to growth suppression, described by a carbon-based stress mortality. If the NPP of the current year is lower than the NPP of the previous year, the current year is count as a stress year. There are species specific probability functions on the base of the number of stress years to calculate the species specific probabilities for tree dead.

Mean diameter at breast height of the trees (d_m)

Diameter growth is modelled based on the carbon which is allocated to the sapwood and heartwood pool and a tree geometry which is based on the concept proposed by Mäkelä (1986). The tree geometry model assumed here is given by a cone for the heartwood below the crown base, which is coated by a ring of sapwood of constant cross sectional area. Inside the crown space the usual cone shall be used.

Broadleaf tree proportion (p_{BL})

Due to the fact that we modelled only monospecific stands, broadleaf tree proportion cannot be calculated at the stand level as the other indicators. We calculated broadleaf tree proportion at the national level with all 69393 plots and at the regional level of the forest regions.

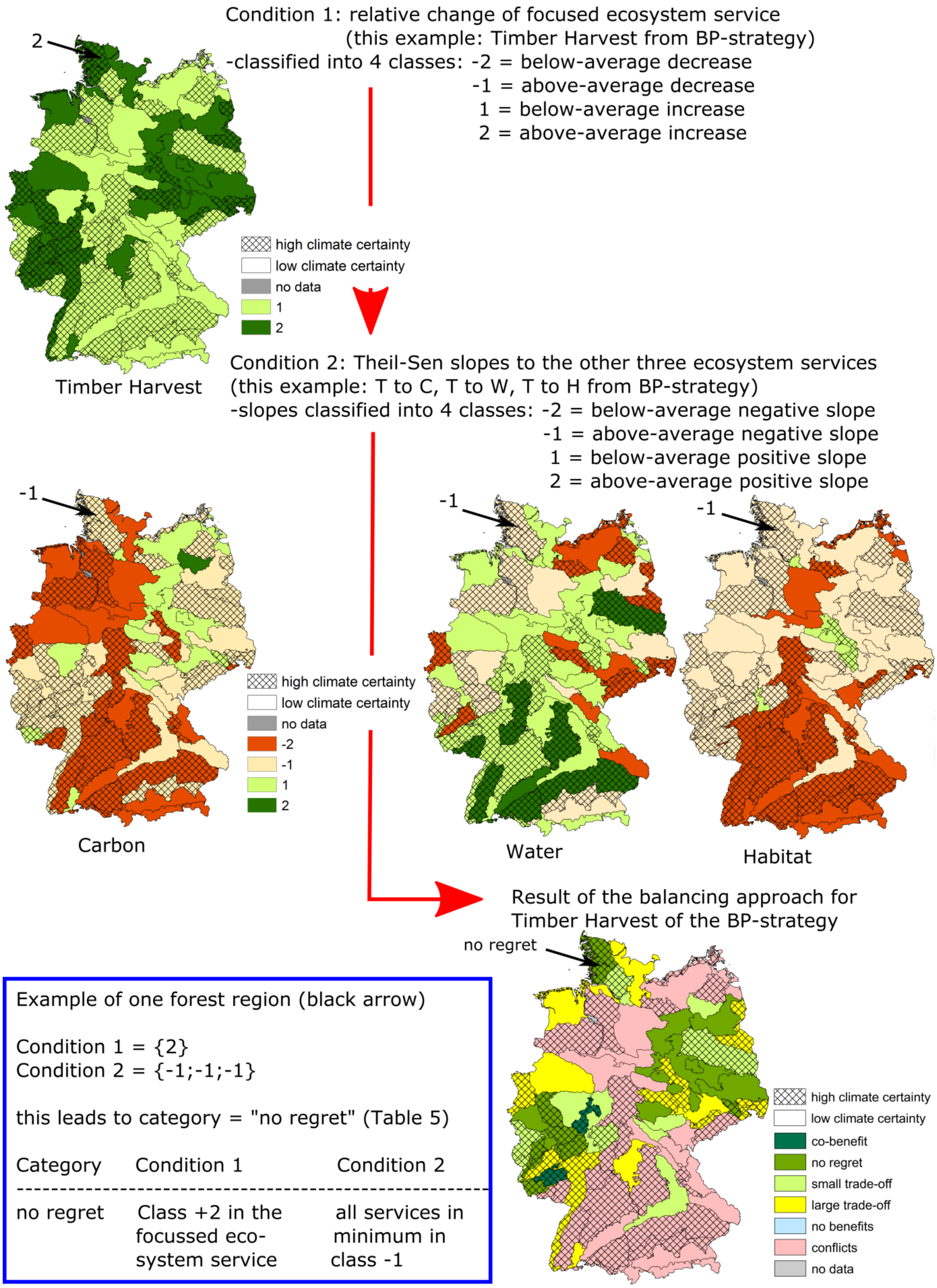

Figure S1: Description of the balancing approach used to draw Figure 3. The example follows one forest region which is classified for condition 1 (Table 5) as class +2 (above-average relative change of Timber Harvest under BP-management). For condition 2 (Table 5) this forest region belongs to

class (-1) for the slope between Timber Harvest and Carbon, Timber Harvest and Water and Timber Harvest and Habitat. This results in the final category “no regret” of Figure 3 (Timber Harvest under BP-management). If more than 90% of all classes were consistent between the climate scenarios we assume that this category has high climate certainty. In case that fewer than 90% of all classes were consistent we assume that the category has low climate certainty.

Absolute values of the single indicators for the historic and future simulation runs

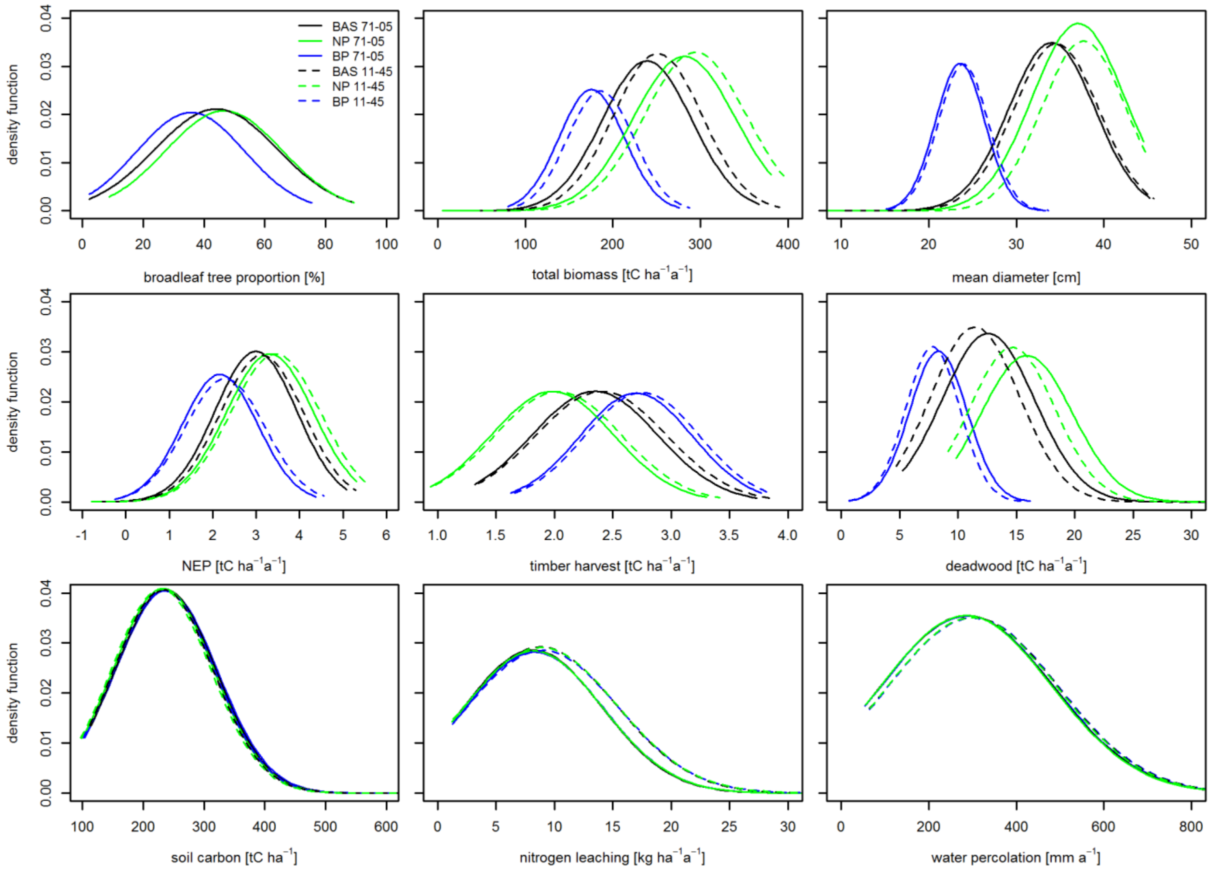

Figure S2: Relative frequency distribution functions (on the basis of the forest regions) for 9 indicators, the baseline management and the NP and BP management strategy, and the historical (1971-2005) and climate change scenarios (2011-2045).

Validation of aggregated model results

The comparison of model results of the baseline management strategy, which reflects the actual management, with BWI^3 data (Thünen-Institut, 2012) aggregated for whole Germany indicates a good overall correspondence for the main tree species. The stem increment (Figure S3 left) is in the range of the reported BWI^3 values except for Douglas fir, where 4C heavily underestimates the stem increment, and for oak stands, where 4C simulates slightly higher results. The results for the harvested timber with the baseline management (BAS) show a good correspondence in case of spruce and pine. But, the amount of harvested timber of the other simulated tree species is significant higher than the BWI^3 values (Figure S3, right). The biomass production (BP) strategy leads to lower stem increments for all species and clearly higher timber harvests compared with the BWI³ data. With this management strategy the timber harvest exceeds the stem increment within the considered time period of 35 years (Figure S3 right). The nature protection (NP) strategy increases the stem increment and reduces clearly the timber harvest compared with the base management. Here the timber harvest is close to the relative to stem increment BWI³ data (Figure S3 right).

The difficulties in the initialisation from average stand values lay in the assumption of the used biomass expansion factors to come from the mean diameter and mean height to the stem volume. Here, we had to adapt the 4C intrinsic biomass functions for coniferous trees by biomass expansion functions reported in the literature (Wirth *et al.* (2004) for Norway spruce, Zianis *et al.* (2005) for Scots pine, and Bartelink (1996) for Douglas fir).

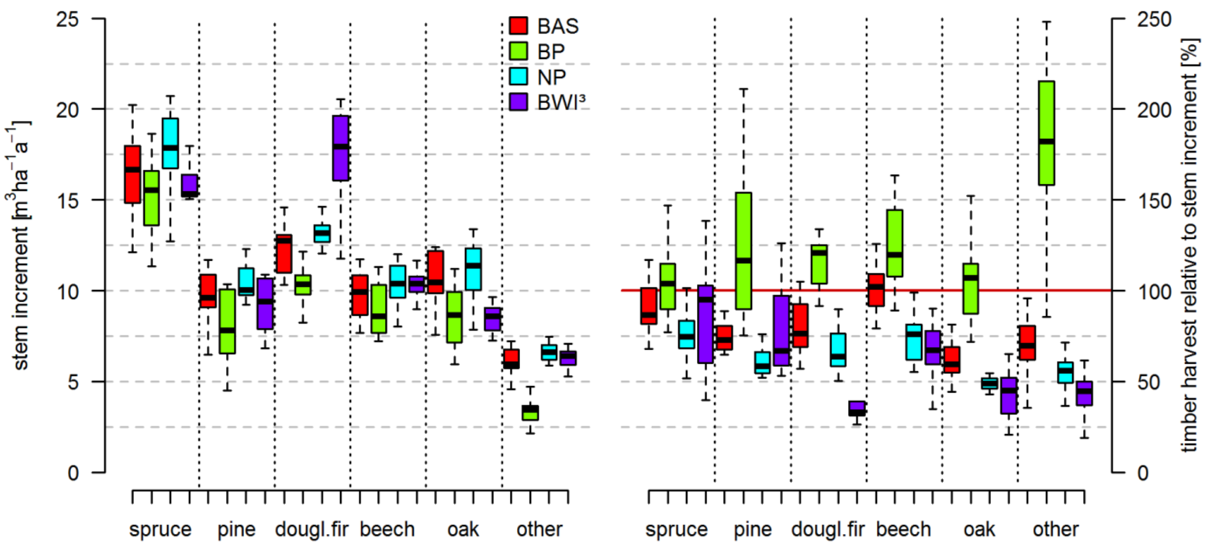

Figure S3: Simulated mean annual stem increment and timber harvest as percentage of stem increment for three management strategies averaged over 13 federal states for the period 1971-2005 in comparison to data of the forest inventory BWI³ (2002-2012).

Figure S4 shows the mean annual sum of timber harvest over all plots for the different tree species for the historic simulation run (1971-2005) and the three management strategies. The implemented management strategies behave as expected and values are close to the reported timber harvest of the national inventory (BWI³, 2002-2012). Also we could observe expected differences between the strategies biomass production (BP, higher timber harvest) and nature protection (NP, lower timber harvest).

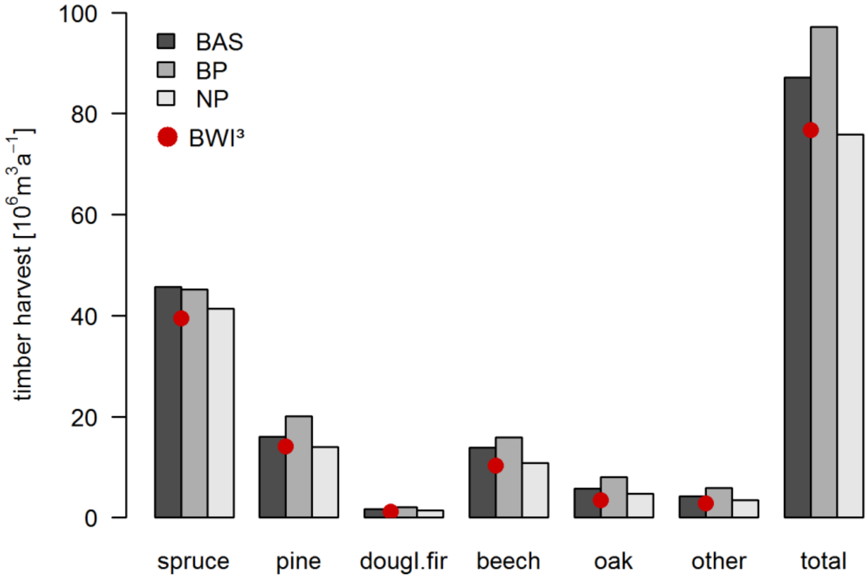

Figure S4: Mean annual simulated timber harvest (1971-2005) as tree species specific sum over all plots in comparison to data of the forest inventory BWI³ (2002-2012).

Analysis of variance of management and climate effects and their interaction on ES results

Table S1: Degree of freedom (Df), Sum of Squares (SQ) and share of total variance for the ecosystem service specific ANOVA models. Forest regions were set as the covariate and climate (14 climate scenarios of Table 1) and management (BP, NP) were the two tested factors with allowing interaction between the two factors. The dependent variable Y is the relative change of the specific ecosystem service with respect to the baseline management and the historic climate.

ANOVA-model	Df	Sum of SQ	share of variance [%]
ES_Water~forest_region+climate*management			
forest_region	84	12782	13.4
management	1	911	1.0
climate	13	4224	4.4
management:climate	13	363	0.4
residuals	2268	77042	80.8
ES_Timber~forest_region+climate*management			
forest_region	84	103002	11.6
management	1	602896	68.2
climate	13	9163	1.0
management:climate	13	564	0.1
residuals	2268	168686	19.1
ES_Carbon~forest_region+climate*management			
forest_region	84	119845	16.3
management	1	293163	40.0
climate	13	13333	1.8

management:climate	13	1094	0.1
residuals	2263	306189	41.7
ES_Habitat~forest_region+climate*management			
forest_region	84	1718128	50.2
management	1	909775	26.6
climate	13	8688	0.3
management:climate	13	1956	0.1
residuals	2268	783901	22.9

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