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Ecosystem sensitivity to land-surface models and leaf area index

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Abstract

The potential sensitivity of ecological models to differences in soil temperature and soil water from land-surface models was evaluated by using model output from the PILPS land-surface model comparison. Simulated soil water and temperatures from the land-surface models were used to calculate the abiotic decomposition factor (ADF). ADF is used by ecosystem models to directly control microbial activity, decomposition of organic matter and nutrient mineralization and indirectly control plant production. The results show that among model differences in soil water and temperature results in large differences in seasonal patterns of ADF, while the annual average ADF varied from 0.24 to 0.32. Differences in soil water had the largest impact on ADF during the summer. The results suggest that using a 0–50 cm soil depth causes ADF to be overestimated and that land-surface models need to include a 0–10 cm soil layer to interface with ecosystem models. ADF is more sensitive to model differences in soil water and temperature than it is in leaf area index (*LAI*), however, reducing *LAI* causes ADF to increase. Most of the models showed that reducing *LAI* caused transpiration water losses to decrease and evaporation water losses to increase.

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1. Introduction

A number of ecosystem models (Pastor and Post, 1986; CENTURY–Parton et al., 1995a,b; TEM–Mellilo et al., 1993; BIOME-BGC–Running and Hunt, 1993; BIOME2–Prentice et al., 1992) have been used to simulate ecosystem dynamics and response to potential climatic change and increased atmospheric CO_2 at regional and global scales. These models simulate plant production, nutrient cycling and soil organic matter dynamics for plant–soil systems. Soil temperature and soil moisture control many ecosystem processes and are simulated by most ecosystem models. The CENTURY model, BIOME2 and the TEM model use relatively simplistic monthly water budget and soil temperature models, while BGC model uses a more sophisticated daily water budget model. There is substantial interest in linking regional and global ecosystem models to atmospheric general circulation models (GCM) which have different land surface parameterization schemes for simulating soil water and soil temperature. Linked GCM–Ecosystem models will use the GCM land surface schemes to simulate soil water and temperature and it is unclear how sensitive the ecosystem models are to the different land surface schemes.

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The major ecosystem processes that are influenced by soil temperature and water include decomposition of dead plant material and soil organic matter (SOM), nutrient mineralization and plant growth. Decomposition of organic matter is performed by different soil microbial organisms which respond to soil water and temperatures in similar ways. Microbial activity generally increases exponentially with increasing temperature as temperature ranges from 0°C to 40°C (Raich and Potter, 1995), while microbes have maximum activity when the soil water filled pore space (WFPS—the fraction of the pores in the soil filled with water) is from 50 to 60%, decreases for high WFPS (> 70%) due to anaerobic conditions (Linn and Doran, 1984; Doran et al., 1988) and decreases for low WFPS (< 40%). Nutrient mineralization (formation of inorganic nitrogen, phosphorus and sulfur) from the soil occurs primarily as a result of decomposition of SOM and plant residue and responds to soil water and temperature in a similar manner. The other major factor which controls nutrient mineralization is the nutrient content of plant litter with higher nutrient content organic matter releasing more nutrients. Plant growth is controlled by soil moisture and temperature with plant growth increasing exponentially as soil temperature increase from 0°C to 15°C, while soil moisture impacts microbial activity and plant growths in a similar way with highest growth rates at 50–60% WFPS.

In this paper we will focus on the sensitivity of the abiotic decomposition factor (ADF) to soil moisture and temperature. All ecosystem models calculate an ADF as a function of the impact of soil moisture and temperature on microbial activity and use this factor as a multiplier when calculating microbial activity and turnover of organic matter. The models use different equations for the impact of soil moisture and temperature on microbial activity, however, most of them use similar functional forms and conceptual framework to calculate ADF (Frissel and Van Veen, 1981). As part of the PILPS soil moisture comparison activity (Shao and Henderson-Sellers, 1996-this issue) different land-surface schemes were compared using the common atmospheric driving variable data set from HAPEX experiment (Goutorbe and Tarrieu, 1991; Goutorbe et al., 1989). The simulated soil moisture and soil temperature resulting from the different land-surface schemes were used to calculate daily values of ADF for each land-surface scheme. In this analysis, we will only compare the models which provided both soil water and tempera-

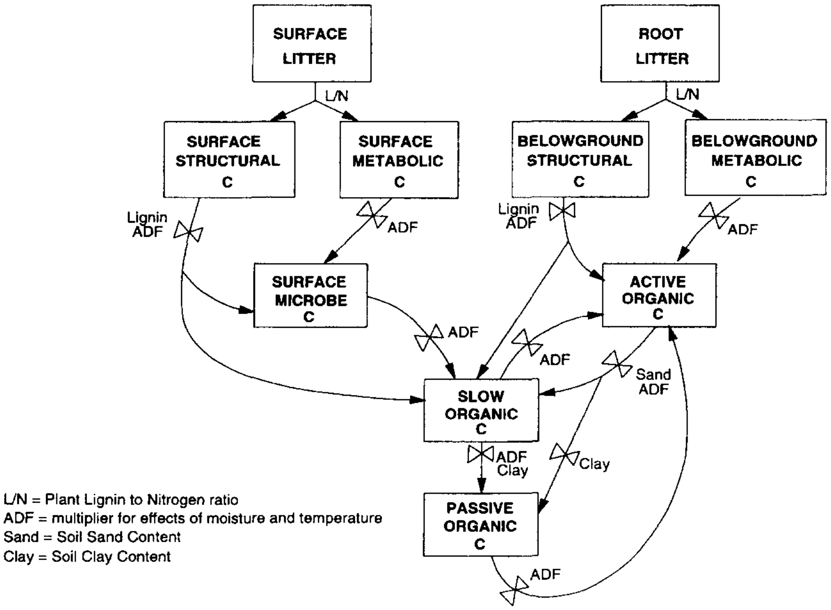

Fig. 1. Flow diagram for the CENTURY model (redrawn from Parton et al., 1994).

ture values into the PILPS database for all of the experiments (many of the models did not provide both soil water and temperature for some of the experiments). Only six of the models provided sufficient data to make consistent comparisons. ADF greatly influences ecosystem dynamics with microbial activity, soil respiration and nutrient mineralization being directly proportional to ADF and soil carbon levels being inversely proportional to ADF. Nutrient mineralization is also one of the primary factors that controls plant production (growth is proportional to nutrient mineralization).

We also evaluate the sensitivity of the land-surface schemes to changes in the leaf area index (*LAI*) of live plants. *LAI* has an impact on soil temperature and soil water content. In general, increasing *LAI* causes soil temperature to decrease (Parton, 1984) as a result of shading of the soil surface by the plant biomass. Plant transpiration rates are proportional to *LAI* for values less than 3–4 and values > 4.0 have relatively little impact on transpiration rate since most of the direct short wave solar radiation has been adsorbed by the plant canopy. In the paper, we will evaluate the impact of changing *LAI* on ADF, and growing season transpiration and evapotranspiration.

2. Model description

Ecosystem models use different equations to calculate the ADF (Frissel and Van Veen, 1981; Melillo et al., 1993; Parton et al., 1994), however, the conceptual basis and shape of the curves are similar for the different models. Ecosystem models divide soil organic matter and plant residue material up into different functional pools but the equations used to represent the decomposition of the organic matter pools are quite similar (Parton et al., 1995a,b). The rate of decomposition of the organic matter pools are generally controlled by an inherent maximum decomposition rate of the different pools, the size of the pools and ADF. The equation used to simulate the decomposition of the CENTURY model organic matter pools (see Fig. 1) is shown in Eq. 1,

$$\frac{d_{c_i}}{d_t} = K_i \cdot C_i \cdot ADF \qquad (1)$$

where C_i is the carbon in the ith organic matter pool ($I =$ 1, 2, 3, 4, 5, 6, 7, 8 for surface and soil structural material, active soil organic matter, surface microbes, surface and soil metabolic material, slow and passive soil organic matter), K_i is the maximum decomposition rate for the *i*th organic matter pool ($I =$ 1, 2, 3, 4, 5, 6, 7, 8–3.9, 4.9, 7.3, 6.0, 14.8, 18.5, 0.2, 0.0045 yr^{-1}) and *ADF* is the combined impact of soil moisture and soil temperature on decomposition rate. Fig. 1 shows that the major factors which control the flow of carbon (C) among the different pools are ADF, plant lignin (L) and nitrogen (N) content, and soil sand and clay content. The L:N ratio controls the split between structural and metabolic C (greater structural C material with higher ratios), the clay content controls the flow of C to passive C (greater for higher clay content), the sand content controls the turnover rate of active C (greater for higher sand content) and slow C formation (less for higher sand content). Each of the flows

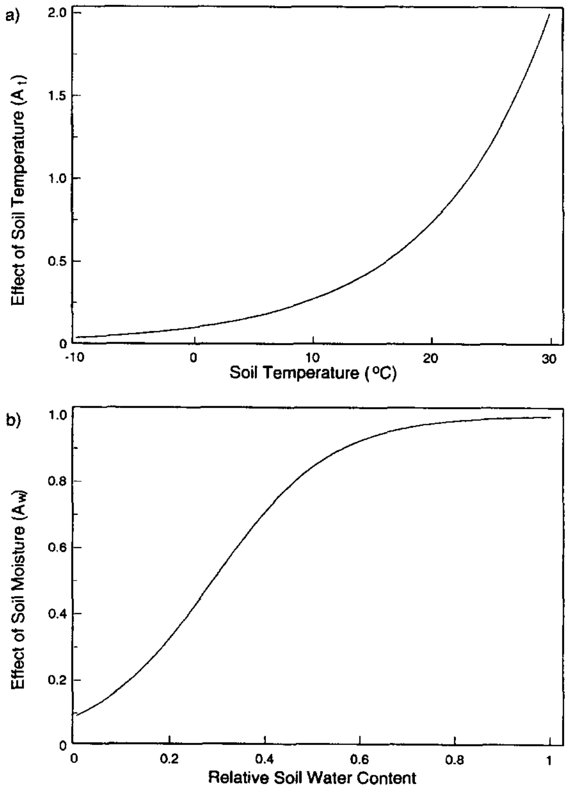

Fig. 2. Effect of (a) soil temperature (A_t) on decomposition and (b) soil moisture (A_w) on decomposition.

of C in Fig. 1 has a microbial respiration flux (C lost as CO_2 due to respiration).

ADF is calculated as a function of the soil moisture factor (A_w) and the soil temperature factor (A_t) using the following equation

$$ADF = A_w \cdot A_t \quad (2)$$

where functional forms of A_w and A_t are shown in Fig. 2. The equation used for A_w is based on a paper by Parton et al. (1988), while the equation for A_t is similar to the equation presented by Raich and Potter, 1995. A_t uses an exponential equation to represent the effect of soil temperature while A_w increases rapidly as the soil relative water content (R_w) increases from 0.2 to 0.6 and is close to 1.0 for R_w values > 0.6. The input into A_w is the R_w for

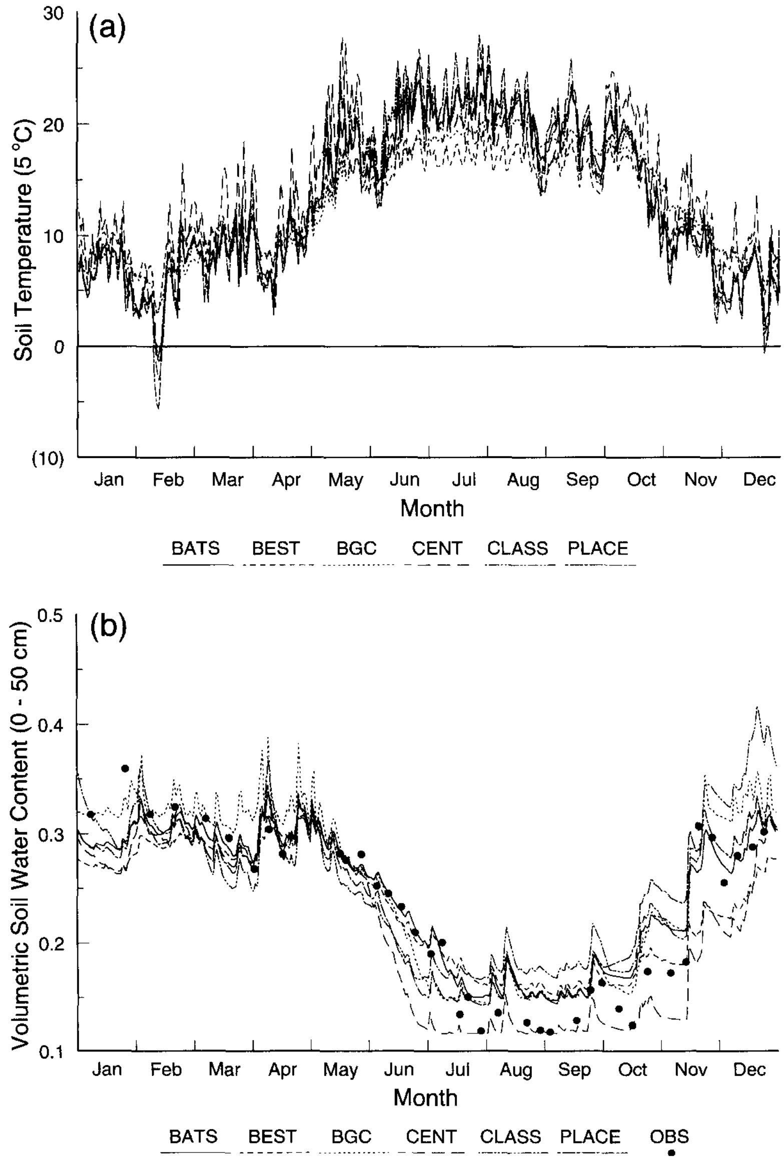

Fig. 3. HAPEX simulation (a) 5 cm soil temperature and (b) simulated vs. observed 0 – 50 cm soil water content for PILPS land-surface models.

the 0–50 cm soil layer. The R_w is the fraction of the soil water available for evapotranspiration and is calculated as a function of the soil field capacity (F_c) and wilting point (F_w) using Eq. 3

$$R_w = \frac{(F_c - w)}{(F_c - F_w)} \quad (3)$$

where F_w is the lowest water content where water can be extracted by evaporation and transpiration water loss (g g^{-1}), F_c is the maximum soil water content after the soil is allowed to drain for twenty-four hours (g g^{-1}) and w is soil water content (g g^{-1}). Field capacity soil water content generally corresponds to the 50–60% water filled pore space. Soil temperature at the 5 cm soil depth is the input into A_t. The same values of F_c and F_w were used for all of the models.

3. Sensitivity of the abiotic decomposition factor

The sensitivity of ADF to differences in the predicted soil temperature and soil water content from the different land-surface schemes were evaluated by comparing calculated ADF values for the models that simulated both soil water and temperature (BATS, BEST, BGC, CENTURY, CLASS, and PLACE). We used model results from the control experiment with the improved versions of the land-surface schemes (Shao and Henderson-Sellers, 1996-this issue). The simulated 0–50 cm soil water (Fig. 3a) shows that all of the model follows the same pattern with high water contents during the winter and spring, rapidly decreasing soil water content in June and early July and low water content at the end of the summer. There are substantial differences in the rate of drying during June and July and the lowest water content at the end of summer. Comparison of observed data (Fig. 3b) with the model results show that most of the model overestimates soil water content at the end of the summer. The results show that all of the models disagree with the observed data for a substantial period of time. Fig. 3a shows the simulated average daily soil temperature (5 cm depth) for the models. The CENTURY model has the highest soil temperature during the winter and spring and the BEST model has the lowest temperature during the summer. The difference among models is generally less than 5°C, however, day to day differences can be as high as 10°C. Unfortunately, we do not have observed data to compare with the simulated results.

The relative impact of model differences in soil temperature and soil moisture were determined by calculating ADF for three separate case studies. The first case study used the BATS soil temperature and the soil moisture values predicted for each of the land-surface schemes. The second case used BATS soil moisture values and soil temperature values predicted for each of the models, while for the third case study predicted soil temperatures and moisture values to calculate ADF. Case study #1 results show (see Fig. 4a) that for fixed temperatures the ADF values are quite similar during the winter and early spring, however, from May until October, difference in soil water contents result in large difference in ADF. BGC and CENTURY had the lowest values of ADF while CLASS had the highest values of ADF. We calculated ADF values with the weekly observed soil water content as our best estimate of the observed ADF values. The results show that all of the models are close to the observed data during the winter and spring, while CENTURY and BGC are closer to the data during the summer and fall months. The results show that most of the models tended to overestimate ADF during the late summer months as a result of high soil water content (see Fig. 3). The CENTURY model correctly predicted the low ADF values during the summer, however, it substantially underpredicted ADF during June.

Fixing the soil water content and using the simulated soil temperature to calculate ADF (Fig. 4b) shows that variance in ADF from soil temperature variations is substantially less than the variance produced by differences in soil water (Fig. 4a) during the summer. Soil temperature differences produced greater variance during the winter and spring months. During the winter and spring the CENTURY model has the highest ADF values (higher soil temperatures), while during the summer the BEST model has the lowest ADF values (lower soil temperatures). Unfortunately, the HAPEX experiment did not measure any soil temperatures and thus we are unable to determine which model results are more realistic. In general, the differences between the soil tempera-

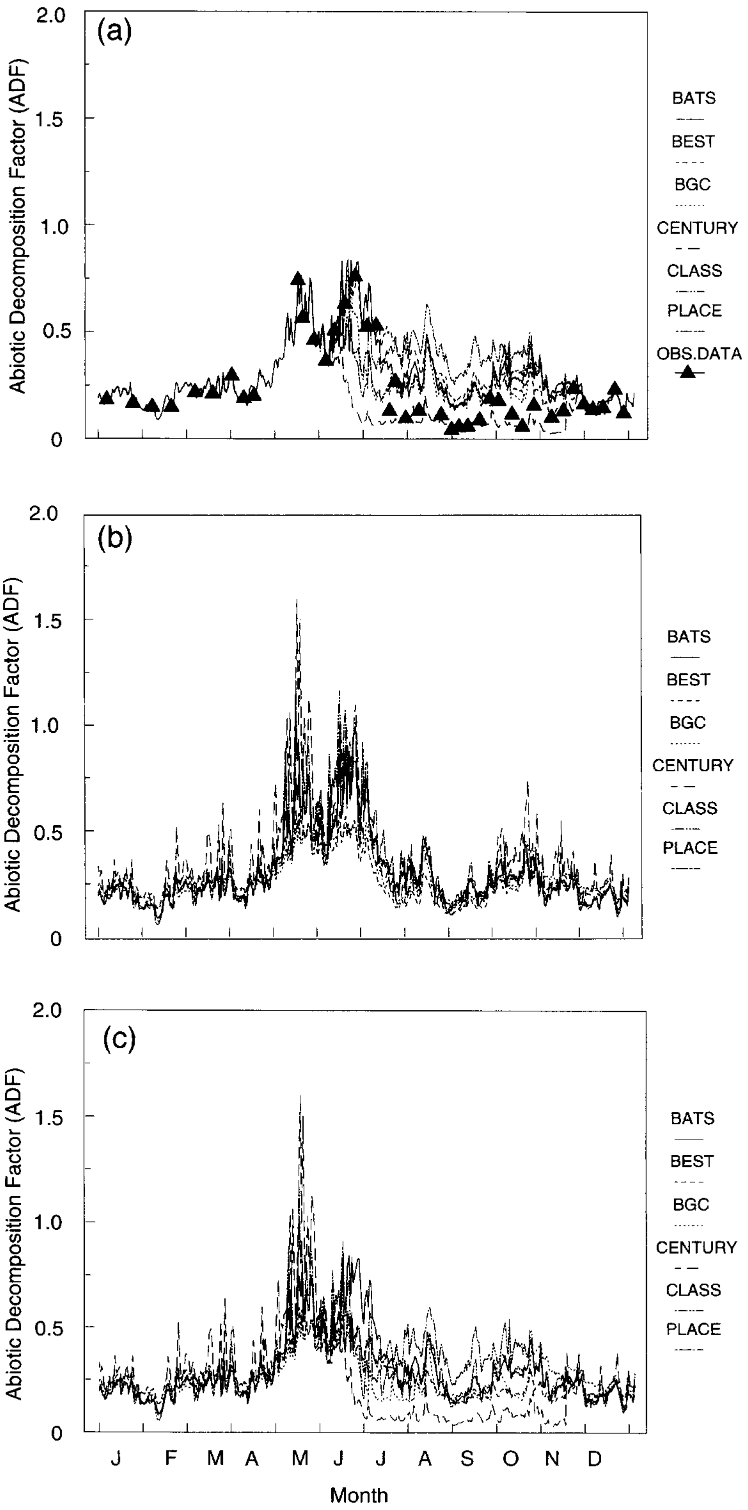
(a)
(b)
(c)
Abiotic Decomposition Factor (ADF)
2.0
1.5
1.0
0.5
0
BATS
BEST
BGC
CENTURY
CLASS
PLACE
OBS.DATA
J F M A M J J A S O N D
Month

Table 1
Annual, growing season and non-growing season average coefficient of variation (CV) of the abiotic decomposition factor (ADF). CV is calculated daily using simulated ADF values for seven land-surface models and averaged for the different periods

Time period	Fixed T (BATS)	Fixed soil water	Varying T and soil water
Growing season	31	19	36
Non-growing season	6	15	17
Annual	18	17	27

tures predicted by the different models is less than the simulated differences in the soil water content.

Using simulated soil temperatures and soil water contents shows that (Fig. 4c) there are large differences in the ADF among the models with the largest differences during late spring and summer months. We attempted to characterize the variance in ADF for the three case studies by calculating the average daily coefficient of variation (CV) of ADF for growing season (Julian dates 120–300) and non-growing season (see Table 1). The results show that for fixed soil temperatures the CV of ADF is low during the non-growing season (6) and quite high during the growing season (31). Fixed soil water content results show that the CV of ADF are similar during the growing and non-growing seasons, that during the non-growing season the fixed water case has higher CV compared to the fixed temperature case, while during the growing season the CV is substantially lower for the fixed water case (compared to the fixed temperature case). As expected, the CV of ADF are highest for case study #3 where both temperature and soil water vary. A summary of the results show that model soil water differences have less impact on ADF values during the winter and spring months, however, during the summer there are substantial differences in ADF values among models. Differences in model simulated soil temperatures result in smaller differences in the ADF values compared to the effect of soil water except during the winter months.

The mean annual ADF values for the land-surface models (Table 2) show that for the fixed temperature study the differences in ADF range from 0.19 for CENTURY to 0.31 for CLASS. With the fixed soil water case, BEST has the lowest value (0.27) and CENTURY the highest (0.36). Varying both temperature and soil moisture reduced the maximum variation in ADF as compared to the fixed temperature case. For the fixed temperature case we compared the results to the mean annual ADF calculated from observed soil water data (0.25) and the results showed that CENTURY underestimated ADF, while all of the other models overestimated ADF to varying degrees. Fig. 4a shows that CENTURY underestimated (low soil water content) ADF during June, all of the other models overestimated (high soil water) during the summer months, while during the non-growing season the models agreed well with the observed data. These results suggest that there are biases in average annual ADF values among models that result from model biases in simulated soil water and temperature.

Table 2
Mean annual abiotic decomposition factor (ADF) for each land-surface model is calculated for Case 1 (fixed temperature), Case 2 (fixed soil water) and Case 3 (varying soil temperature and soil water). Case #1 is compared to ADF value calculated with BATS temperature and HAPEX observed soil water content (0–50 cm)

Case study	BATS	BEST	BGC	CENT	CLASS	PLACE	Observed soil water
Fixed T	0.30	0.30	0.27	0.19	0.31	0.28	0.25
Fixed soil water	0.30	0.27	0.28	0.36	0.31	0.31	–
Varying T, soil water	0.30	0.26	0.25	0.24	0.32	0.28	–

Fig. 4. Simulated seasonal patterns in the abiotic decomposition factor for the land-surface models for (a) Case study #1 with fixed soil temperature, (b) Case study #2 with fixed soil water contents, and (c) Case study #3 where soil temperature and soil water varied.

4. Soil structure effect on ADF

We used the aggregated 0–50 cm soil water content to calculate ADF because there was substantial differences among the land surface models in the number and depth of the soil water layers. This section will evaluate how differences in structure of the soil water models could impact ADF by using the observed soil water data (measured weekly at 10 cm increments down to 150 cm depth) from different soil depths to calculate ADF. The observed data (0–10 cm, 10–20 cm, 20–50 cm and 0–50 cm depths) was linearly interpolated to a daily time series of soil water for the four depths and then combined with the simulated BATS soil temperature (5 cm depth) to calculate ADF (Fig. 5). The results show that using different observed soil water layers to calculate ADF has little effect on ADF during winter and spring, however, there are substantial differences during the summer and fall. The HAPEX site is fairly wet for all soil layers during the winter and spring months (see Fig. 4b), however, during the summer the soil dries out most rapidly in the near surface layers (0–10 cm and 10–20 cm depth) until all of the layers are dry by the end of July. During the end of the summer, surface layers are rewetted from irrigation and rainfall but the deep layers remain dry. This pattern is reflected in lower ADF values for near surface soil layers during the early summer dry down, and higher ADF values for near surface layers late in the summer.

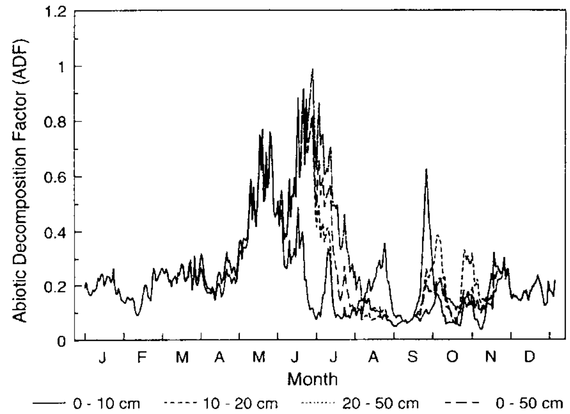

Fig. 5. Abiotic decomposition factor calculated with BATS soil temperature and observed soil water content in 0–10, 10–20, 20–50 and 0–50 cm depths.

Table 3
Simulated growing season (day 140 to 280), non-growing season and annual ADF calculated using the observed HAPEX 0–10, 10–20, 20–50 and 0–50 cm soil water data

Soil depth	Non-growing season	Growing season	Annual
0–10	0.19	0.24	0.22
10–20	0.20	0.29	0.25
20–50	0.20	0.34	0.27
0–50	0.20	0.31	0.25

The mean annual, growing season and non-growing season values of ADF for the different soil layers were calculated (Table 3) and show there were little differences among layers during the non-growing season, however, during the growing season (Julian days 140–280) ADF is lowest for the 0–10 cm layer (0.24) and highest for 20–50 cm layer (0.34). The ADF for the 0–50 cm layer has higher values than the 0–10 cm layer (25%) and is more similar to the 10–20 and 20–50 cm layers. A high percentage (> 50%) of the microbial respiration and nutrient mineralization occurs in the 0–10 cm layer (Schimel and Parton, 1986) and thus the 0–10 cm layer ADF is the most influential on ecosystem nutrient and carbon dynamics. This suggests that land surface models need to represent near surface soil water dynamics and that using coarse soil layer structure will result in overestimates of the ecosystem ADF. These results show that the soil water layer structure has a substantial impact on the calculated ADF and that aggregating over deeper soil depths and using soil water content from deeper soil layers generally result in higher values of ADF.

5. Sensitivity to leaf area index

Leaf area index (*LAI*) is one of the important variables simulated by ecosystem models that influence land-surface models. *LAI* is generally proportional to the biomass of live leaves (needles and leaves) and are higher for ecosystems that have high plant production. The major factors that control plant production are soil temperature and moisture, solar radiation and available soil nutrients. *LAI* impacts the land-surface models by influencing the surface roughness, transpiration rate and the soil water and temperature. Increasing *LAI* results in higher surface roughness, transpiration rate, light and water interception by the plant canopy and lower soil evaporation rate and soil temperatures. We have evaluated the sensitivity of the land surface schemes by comparing model results from the control case study with a model run where the *LAI* was reduced by one half. The soya crop was grown for the control run and the *LAI* follows a seasonal pattern with zero *LAI* and plant biomass during the winter and early spring. The crop is planted in early May and the *LAI* increases rapidly to > 3.0 by the end of June and has a peak value of 4.0 from July until October when the crop is harvested. The model output variables include growing season (140–250 days) soil water and temperature, transpiration rate, ADF, and total evapotranspiration rate. The results (Table 4) show that decreasing *LAI* caused ADF to increase, transpiration rate to decrease (except for BATS) and total evapotranspiration to increase or decrease slightly. The combined impact of reducing soil temperature and increasing soil water (data not shown) caused ADF to increase. The comparison of transpiration and evapotranspiration data show that the reduction in transpiration was compensated for with an increase in evapotranspiration water loss. Comparison of the results from the different land-surface models show that most models behave in a similar way, however, there are substantial differences in the sensitivity of the models to change in *LAI* with BATS being insensitive to LAI changes. This suggests there are differences in the equations used to represent the impact of *LAI* on the land surface processes and that the ecological models are sensitive to these differences.

6. Discussion

The major objective of this paper was to evaluate the potential sensitivity of ecological models to differences in predicted soil temperature and water from land-surface models. The comparison of predicted soil temperature and soil water patterns for different models shows that there are substantial day to day variations and biases among the models represented in PILPS. The predicted soil water contents (Fig. 3) agreed fairly well during the winter and spring months and were quite different during the summer. Comparison with observed soil water data shows that the models did an adequate job of simulating soil water during the winter, while most of the models overestimated soil water during the summer. Some models do a better job simulating the seasonal soil water pattern, however, all of the models disagree with the observed data for part of the year.

The simulated differences in soil water and temperature predicted by the land-surface models had a significant impact on the abiotic decomposition factor, which controls soil decomposition and nutrient mineralization. The biases in the simulated soil temperature and water among the models had a substantial impact on the mean annual ADF (values ranging from 0.24 to 0.32 for the case #3 (Table 4). ADF was fairly similar among models during winter and spring, however, during the summer there were substantial differences in ADF among models with most models overestimating ADF during the summer. Variations among models in simulated soil temperatures were less than those observed for soil water with more variation in ADF resulting from differences in simulated soil water content. The model

Table 4

Simulated percent change in growing season (day 140–280) abiotic decomposition factors, and change in growing season transpiration (cm H_2O) and evapotranspiration (cm H_2O) resulting from a reduction in Leaf Area Index (1/2 control values)

Variable	BATS	ISBA	CENTURY	SSIB	PLACE
ADF	+2.0	–	+9.6	–	+4.5
Transpiration	+0.2	−3.32	−1.8	−2.75	−3.1
Evapotranspiration	+0.9	−2.08	−0.07	+0.9	+0.132

differences in the seasonal patterns of ADF and in the mean annual ADF would have a substantial impact on the dynamics of ecosystem models. For example, the overestimated ADF by many of the models during the summer and fall would result in an overestimate of microbial respiration, nutrient mineralization, and plant production during that time period. The model differences in mean annual ADF would cause the soil organic matter levels (SOM) to be higher for models with low ADF and lower for models with high ADF (SOM levels are proportional to ADF and the amounts of C added to the soil—Parton et al., 1994).

ADF was calculated using observed soil water data from different soil depths and the results show that the seasonal patterns and mean annual values are sensitive to soil depth. The 0–10 cm soil depth had the lowest ADF (Table 3) and ADF increased for the deeper soil layers. Most (> 50%; Schimel and Parton, 1986) of the nutrient mineralization and microbial activity occurs in the 0–10 cm layer suggesting that detailed layer structure is needed to correctly simulate ADF. The results show that aggregating the near surface soil water layers into 0–50 cm depth results in higher values of ADF compared to the 0–10 cm values, which is the most representative for controlling decomposition.

Leaf area index is one of the major inputs from ecological models into land-surface models. *LAI* is a function of soil temperature and soil water, solar radiation and nutrient availability. Reducing *LAI* tended to increase ADF and decrease transpiration rate. The sensitivity of the land-surface model was quite different and the reasons for these differences is not clear. In general, ADF is more sensitive among model simulated differences in soil water and temperature than to changes in the *LAI*.

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References

Doran, J.W., Mielke, L.N. and Stamatiadis, S., 1988. Microbial activity and N cycling as regulated by soil water-filled pore space. Proc. 11th Conf. Int. Soil Tillage Res. Org., 1, Edinburgh, pp. 49–54.

Frissel, M.J. and Van Veen, J.A. (Editors), 1981. Simulation of Nitrogen Behaviour of Soil-Plant Systems. PUDOC, Centre Agric. Publ. Doc., Wageningen.

Goutorbe, J.P. and Tarrieu, C., 1991. HAPEX–MOBILHY data base. In: Schmugge and Andre (Editors), Land Surface Evaporation. Springer, Berlin, pp. 403–410.

Goutorbe, J.P., Noilhan, J., Cuenca, R. and Valancogne, C., 1989. Soil moisture variations during HAPEX–MOBILHY. Ann. Geophys., 7: 415–426.

Linn, D.M. and Doran, J.W., 1984. Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and non-tilled soils. Soil Sci. Soc. Am. J., 48: 1267–1272.

Melillo, J.M., McGuire, A.D., Kicklighter, D.W., Moore III, B., Vorosmarty, C.J. and Schloss, A.L., 1993. Global climate change and terrestrial net primary production. Nature, 363: 234–240.

Parton, W.J., 1984. Predicting soil temperatures in a shortgrass steppe. Soil Sci., 138: 93–101.

Parton, W.J., Ojima, D.S., Cole, C.V. and Schimel, D.S., 1994. A general model for soil organic matter dynamics: Sensitivity to litter chemistry, texture and management. In: Quantitative Modelling of Soil Forming Processes. SSSA Spec. Publ., 39.

Parton, W.J., Scurlock, J.M.O., Ojima, D.S., Schimel, D.S., Hall, D.O. and SCOPEGRAM Group Members, 1995a. Impact of climate change on grassland production and soil carbon worldwide. Global Change Biol., 1: 13–22.

Parton, W.J., Ojima, D.S. and Schimel, D.S., 1995b. Models to evaluate soil organic matter storage and dynamics. In: M.R. Carter (Editor), Structure and Organic Matter Storage in Agricultural Soils. CRC Press, in press.

Pastor, J. and Post, W.M., 1986. Influence of climate, soil moisture and succession on forest carbon and nitrogen cycles. Biogeochemistry, 2: 3–27.

Prentice, I.C., Cramer, W., Harrison, S.P., Leemans, R., Monserud, R.A. and Solomon, A.M., 1992. A global biome model based on plant physiology and dominance, soil properties and climate. J. Biogeogr., 19: 117–134.

Raich, J.W. and Potter, C.S., 1995. Global patterns of carbon dioxide emissions from soils. Global Biogeochem. Cycles, 9: 23–36.

Running, S.W. and Hunt Jr., E.R., 1993. Generalization of a forest ecosystem process model for other biomes, BIOME-BGC, and an application for global-scale models. In: J.R. Ehleringer and C. Field (Editors), Scaling Processes Between Leaf and Landscape Levels. Academic Press, Orlando, pp. 141–158.

Schimel, D.S. and Parton, W.J., 1986. Microclimatic controls of nitrogen mineralization and nitrification in shortgrass steppe soils. Plant Soil, 93: 347–357.

Shao, Y. and Henderson-Sellers, A., 1996. Validation of soil moisture simulation in landsurface parameterisation schemes with HAPEX data. Global Planet. Change, 13: 11–46.