

Australia (19). Thus, the widespread increase in growing season length may be a result of shortened and more divergent life histories.

Monitoring of the peak season duration through observations of surface greenness can be used to determine how individual species respond to an extended growing season (see the table). Changes in the duration of species' life histories have consistent effects on the peak season duration. Constant or shortened life histories decrease the peak season duration. Alternatively, if the shift in timing occurs because of a longer life history, the duration of the peak season will remain constant. Finally, the peak season duration will only increase if species extend their life cycles by more days than the growing season is lengthened.

Daily measurements of surface greenness from ground-based platforms are increasingly used in phenological studies (22, 23), including those in the tropics (24). These data may be sufficient to characterize the duration of peak season in regions where canopy closure corresponds with the onset of peak leaf area. However, models that relate leaf density to greenness may be needed where this does not

occur. Piecewise linear models can be fit to the data to determine the duration of peak season via the onset of peak leaf area and senescence. Observations of surface greenness in phenological networks would create continental-scale data sets that could be compared to regional trends in climate and to satellite data.

Although an extended growing season may lead to increased plant production, this is less likely if individual species shorten their life histories. Shortened, more divergent life histories may lead to gaps in the availability of resources for pollinators and herbivores (11) and may facilitate the establishment of invasive species (12). Nutrient losses during the growing season could also increase through decreased species complementarity (9). Thus, the contrasting changes in the duration of the growing season and species' life cycles are consistent, but increase the likelihood that climate warming is altering the structure and function of ecological communities, perhaps adversely.

#### References

1. N. Delbart *et al.*, *Global Change Biol.* **14**, 603 (2008).
2. A. Menzel *et al.*, *Global Change Biol.* **12**, 1969 (2006).
3. R. B. Myneni, C. D. Keeling, C. J. Tucker, G. Asrar, R. R. Nemani, *Nature* **386**, 698 (1997).

4. C. Parmesan, *Global Change Biol.* **13**, 1860 (2007).
5. C. Rosenzweig *et al.*, *Nature* **453**, 353 (2008).
6. L. M. Zhou *et al.*, *J. Geophys. Res.* **106**, 20069 (2001).
7. B. W. Heumann, J. W. Seaquist, L. Eklundh, P. Jonsson, *Remote Sens. Environ.* **108**, 385 (2007).
8. P. R. Petrie, V. O. Sadras, *Aust. J. Grape Wine Res.* **14**, 33 (2008).
9. E. E. Cleland, N. R. Chiariello, S. R. Loarie, H. A. Mooney, C. B. Field, *Proc. Natl. Acad. Sci. U.S.A.* **103**, 13740 (2006).
10. R. D. Hollister, P. J. Webber, C. Bay, *Ecology* **86**, 1562 (2005).
11. E. S. Post, C. Pedersen, C. C. Wilmers, M. C. Forchammer, *Ecology* **89**, 363 (2008).
12. R. A. Sherry *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **104**, 198 (2007).
13. D. W. Inouye, *Ecology* **89**, 353 (2008).
14. A. Jentsch, J. Kreyling, J. Boettcher-Treschkow, C. Beierkuhnlein, *Global Change Biol.* **15**, 837 (2009).
15. A. M. Arft *et al.*, *Ecol. Monogr.* **69**, 491 (1999).
16. J. Penuelas *et al.*, *Ecosystems* **7**, 598 (2004).
17. L. E. Rustad *et al.*, *Oecologia* **126**, 543 (2001).
18. M. D. Schwartz, R. Ahas, A. Aasa, *Global Change Biol.* **12**, 343 (2006).
19. F. C. Jarrad, C. Wahren, R. J. Williams, M. A. Burgman, *Aust. J. Bot.* **56**, 617 (2008).
20. X. Morin *et al.*, *Global Change Biol.* **15**, 961 (2009).
21. R. Gazal *et al.*, *Global Change Biol.* **14**, 1568 (2008).
22. A. D. Richardson *et al.*, *Oecologia* **152**, 323 (2007).
23. K.-P. Wittich, M. Kraft, *Int. J. Biometeorol.* **52**, 167 (2008).
24. C. E. Doughty, M. L. Goulden, *J. Geophys. Res.* **113**, G00B06 (2008).

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## ECOLOGY

# Phenology Feedbacks on Climate Change

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Climate warming has advanced the biological spring and delayed the arrival of biological winter (1, 2). These changes in the annual cycle of plants and the lengthening of the green-cover season have many consequences for ecological processes, agriculture, forestry, human health, and the global economy (3). Studies on vegetation-atmosphere interactions (4) and particularly on the impact of leaf emergence on climate (5–9) suggest that the phenological shifts in turn affect climate. The magnitude and sign of this effect are unknown but depend on water availability and regional characteristics.

The earlier presence of green land cover and the delay in autumnal senescence and leaf fall of deciduous canopies may alter the seasonal climate through the effects of biogeo-

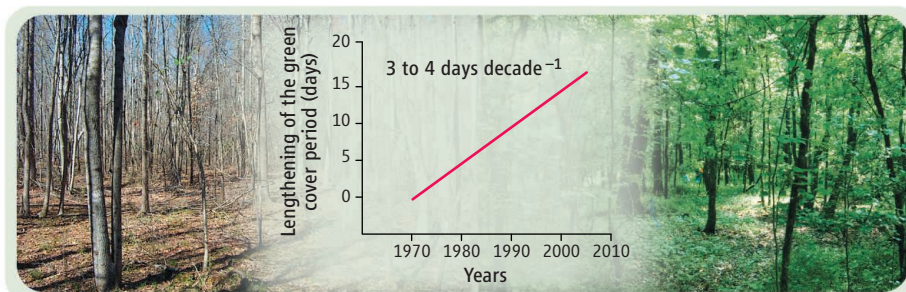
chemical processes (especially photosynthesis and carbon sequestration) and physical properties (mainly surface energy and water balance) of vegetated land surfaces.

CO<sub>2</sub> uptake is the main biogeochemical effect. An extended plant activity season increases biospheric CO<sub>2</sub> uptake (3) and thus decreases the current rise of atmospheric CO<sub>2</sub> concentration and its influence on the green-

A longer growing season as a result of climate change will in turn affect climate through biogeochemical and biophysical effects.

house effect (1). The extended plant activity also further increases the total annual emission of biogenic volatile organic compounds (BVOCs) (10). These increased emissions may also contribute to the complex processes associated with global warming (10).

Although the atmospheric lifetime of BVOCs is short, they have an important influence on climate through aerosol formation and



**Phenology and climate.** The change from a dormant winter to a biologically active spring landscape has numerous biogeochemical and biophysical effects on climate. Earlier leaf unfolding and delayed leaf fall as a result of global warming (graph) (3, 17) will thus affect climate change itself.

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direct and indirect greenhouse effects. BVOCs generate large quantities of organic aerosols (11, 12) that could affect climate by forming cloud condensation nuclei. The result should be a net cooling of Earth's surface during the day because of radiation interception. Furthermore, the aerosols diffuse the light received by the canopy, increasing CO<sub>2</sub> fixation. However, BVOCs also increase ozone production and the atmospheric lifetime of methane, enhancing the greenhouse effect of these gases. Whether the increased BVOC emissions will cool or warm the climate depends on the relative weights of the negative (increased albedo and CO<sub>2</sub> fixation) and positive (increased greenhouse action) feedbacks (10).

A longer presence of the green cover in large areas should also alter physical processes such as albedo, latent and sensible heat, and turbulence. Observations in the Eastern United States show that springtime air temperatures are distinctly different after leaves emerge (5). Latent heat flux increases and the Bowen ratio (the ratio of sensible to latent heat) decreases after leaf emergence. As a result, the increased transpiration cools and moistens air, and the spring temperature rise drops abruptly (5, 6). The coupling between land and atmosphere also becomes more efficient, because an increase in surface roughness lowers aerodynamic resistance, generates more turbulence and higher sensible and latent heat fluxes, and leads to a wetter, cooler atmospheric boundary layer (7).

The longer presence of green cover thus generates a cooling that mitigates warming by sequestering more CO<sub>2</sub> and increasing evapotranspiration. However, this carbon fixation and evaporative cooling decline if droughts become more frequent or when less water is available later in the summer. In fact, an early onset of vegetation green-up and a prolonged period of increased evapotranspiration seem to have enhanced recent summer heat waves in Europe by lowering soil moisture (8, 9). The depletion of summer soil moisture strongly reduced latent cooling and thereby increased surface temperature (9) and likely reduced summer precipitation (13).

Furthermore, reduced albedo after leaf emergence may warm the land surfaces—especially those with high albedo, such as snow-covered areas—at spatial scales of hundreds and even thousands of kilometers. The lengthening of the green-cover presence can hence either dampen or amplify global warming, depending on water availability and regional characteristics. In wet regions and seasons, additional water vapor may form clouds that contribute to surface cooling and increased rainfall in nearby areas, whereas in

drier conditions, a longer presence of the green cover may warm regional climate by absorbing more sunlight without substantially increasing evapotranspiration.

There are many unknowns in the combined impacts of all these biogeochemical and biophysical processes on local, regional, and global climate. Phenology models used in global climate simulations are highly empirical and use a few local-scale findings that represent only a fraction of the global bioclimatic diversity, and that therefore preclude global coverage validation. As a result, the predicted timing of temperate and boreal maximum leaf area may be too late by up to 1 to 3 months, resulting in an underestimate of the net CO<sub>2</sub> uptake during the growing season (14). Satellite data assimilation can be of great help to minimize the large differences between observed and predicted spatiotemporal phenological patterns (15, 16).

Future studies should aim to quantify and understand the effects of earlier leaf unfolding and later leaf fall on temperature, soil moisture, and atmospheric composition and dynamics; this information will help to improve the representation of phenological changes in climate models and thus increase the accuracy of forecasts. Reinterpreting existing data sets (17) and advances in remote sensing techniques, in combination with con-

tinued long-term ground observations, will be crucial for this task.

#### References and Notes

1. IPCC, *The Physical Science Basis: Contribution of Working Group I to the Fourth Assessment of the Intergovernmental Panel on Climate Change* (Cambridge Univ. Press, Cambridge, 2007).
2. H. Steltzer, E. Post, *Science* **324**, 886 (2009).
3. J. Peñuelas, I. Filella, *Science* **294**, 793 (2001).
4. G. B. Bonan, *Science* **320**, 1444 (2008).
5. M. D. Schwartz, *J. Climate* **9**, 803 (1996).
6. D. R. Fitzjarrald, O. C. Acevedo, K. E. Moore, *J. Climate* **14**, 598 (2001).
7. G. B. Bonan, *Ecological Climatology: Concepts and Applications* (Cambridge Univ. Press, Cambridge, 2nd ed., 2008).
8. B. Zaitchik, A. K. Macalady, L. R. Bonneau, R. B. Smith, *Int. J. Climatol.* **26**, 743 (2006).
9. E. Fischer, S. Seneviratne, P. Vidale, D. Lüthi, C. Schär, *J. Climate* **20**, 5081 (2007).
10. J. Peñuelas, J. Llusà, *Trends Plant Sci.* **8**, 105 (2003).
11. M. Claeys *et al.*, *Science* **303**, 1173 (2004).
12. A. Laaksonen *et al.*, *Atmos. Chem. Phys.* **8**, 2657 (2008).
13. X. Jiang, G.-Y. Niu, Z.-L. Yang, *J. Geophys. Res.* **114**, D06109 (2009).
14. J. T. Randerson *et al.*, *Global Change Biol.*, 10.1111/j.1365-2486.2009.01912.x (2009).
15. R. Stöckli *et al.*, *J. Geophys. Res.* **113**, G04021 (2008).
16. M. F. Garbulska, J. Peñuelas, D. Papale, I. Filella, *Global Change Biol.* **14**, 2860 (2008).
17. A. Menzel *et al.*, *Global Change Biol.* **12**, 1969 (2006).
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## OCEAN SCIENCE

# Ice Sheet Stability and Sea Level

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How much will sea levels rise if the West Antarctic Ice Sheet becomes unstable?

Volume changes in the Antarctic Ice Sheet are poorly understood, despite the importance of the ice sheet to sea-level and climate variability. Over both millennial and shorter time scales, net water influx to the ice sheet (mainly snow accumulation) nearly balances water loss through ice calving and basal ice shelf melting at the ice sheet margins (1). However, there may be times when parts of the West Antarctic Ice Sheet (WAIS) are lost to the oceans, thus raising sea levels. On page 901 of this issue, Bamber *et al.* (2) calculate the total ice volume lost to the oceans from an unstable retreat of WAIS, which may occur if the part of the ice sheet that overlies sub-marine basins is ungrounded and moves to

a new position down the negative slope (see the figure).

More than 90% of the ice delivered from Antarctica to the oceans comes from fast-moving ice streams and outlet glaciers, with velocities of tens to hundreds of meters per year (3). The outflux is controlled in part by the intrinsic resistance to flow provided by stresses at the bedrock or as internal shear. Also controlling the flow rate are gravitational driving forces and mechanical buttressing at the seaward margins provided by floating ice shelves (4).

How intrinsically stable is the ice sheet, given the marine-based bottom topography and geometry in much of the interior of West Antarctica and the potential loss of buttressing provided by ice shelves (5, 6)? Satellite data have shown dramatic changes in West Antarctica, as some important out-

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