roughly equal to natural erosion.

Sparring aside, a recent set of analyses* has helped clarify the link between soil degradation and tapered growth in crop yields. One study, led by Christoffel den Biggelaar of Appalachian State University in Boone, North Carolina, combined erosion rates, estimated by soil type and climate, with data from hundreds of field studies for various crops. The team estimated global average potential yield losses at 0.3% a year, compared to Pimentel’s 8% for the United States. Recognizing that most farmers have incentives to counter these losses—for example, by using better tilling methods—the actual decline may be as low as 0.1%, USDA’s Wiebe says. But that figure is not trivial, he cautions. Growth rates of global cereal yields, which have grown at a brisk 2% per year since the 1960s, are expected to rise at a slower rate in coming decades. As that happens, Wiebe says, 0.1% “gets to be a more important number.”

Moreover, the reasonably rosy global picture glosses over disturbing regional trends. Degradation is clearly cutting into yields in parts of Africa, South Asia, and Latin America, notes Forest Trends analyst Sara Scherr. “The critical issue,” she says, “is where are the places in the world” where soil degradation matters most. A USDA analysis found that if struggling regions could reduce degradation and thereby boost crop-yield growth by a mere 0.1% per year, the number of malnourished people would fall by 5%, or 37 million, over a decade.

A fertile future?

There’s no lack of technological fixes for reversing soil degradation. In the United States, for instance, no-till farming has helped reduce water erosion by over 40% since 1982, Pimentel notes. And in developing countries, strategies such as sowing cover crops and planting trees have been shown to restore soil fertility and stem erosion. But these solutions can’t be imposed top-down (Science, 21 November 2003, p. 1356). Terracing, for example, has failed in many places, including Haiti, because it is too expensive for most farmers.

Although the United Nations funds some efforts to disseminate approaches that work, major aid organizations, such as the World Bank, have slashed agricultural budgets over the past 2 decades in favor of addressing urban projects, Scherr says. But the pendulum appears to be swinging back to rural development. For example, soil health tops a list of priorities being assembled by the U.N. Millennium Project’s hunger task force, which aims to halve the number of starving people by 2015, says co-chair Pedro Sanchez of Columbia University’s Earth Institute. Soil degradation, he says, is “the main constraint to reducing hunger” in Africa.

The biggest looming issue may be global warming. Lal notes that erosion already contributes to warming, because some of the carbon in soil-laden water running off fields wafts into the atmosphere. Yet fields could sop up some of this carbon, Lal says, if farmers adopt practices to reduce erosion and retain nutrients, as is encouraged by the Kyoto Protocol on climate change (see p. 1623). Inevitably, “a hotter world is likely to have less organic matter” in its soils, Duke’s Schlesinger notes. Such vital nutrients decompose as temperatures rise, releasing carbon. Deserts will also expand as the interiors of continents become drier. Erosion rates could rise if soils dry out and storms increase, Lal says. “The risks of soil degradation are going to go up, but how much, we don’t know,” he says.

Soil degradation is no longer seen as a matter of “global survival,” says Wiebe. But “it’s still an issue. It will keep coming back.” In a warming world, it could come back to haunt us.

—JOCELYN KAISER

NEWS

Defrosting the Carbon Freezer of the North

The perpetually frozen soils of the Arctic and boreal regions are thawing at unprecedented rates. It’s unclear what this bodes for global warming.

When Phil Camill goes looking for frozen soil in the spruce forests of northern Manitoba each summer, he finds less and less each year. Instead of rock-hard permafrost, he discovers drenched soil, dying trees, and ever-expanding, mossy bogs. The ground is so saturated that it quakes underfoot, says Camill, a plant ecologist at Carleton College in Northfield, Minnesota: “It’s like walking on a trampoline.”

Across huge swaths of the Arctic, permafrost is warming to record high temperatures. “It’s really happening almost everywhere,” says Vladimir Romanovsky, a geophysicist at the University of Alaska, Fairbanks. The pace has shocked researchers—and it’s accelerating. In Manitoba, the southern edge of Canada’s permafrost, the thaw rate has nearly tripled over 4 decades; this patchy permafrost is now receding up to 1 centimeters per year, and in a forthcoming paper in Climatic Change, Camill predicts that Manitoba will lose most of its permafrost within a century. Even in the far north, where soil deposits are thicker and colder, much permafrost has warmed to the brink of meltdown. That’s a major concern for residents: “Settling of the ground has already dammed buildings, pipelines, and other infrastructure in Alaska and Siberia (Science, 30 August 2002, p. 1493).”

But widespread permafrost melting could have grave consequences well beyond the far north. No one knows exactly how much carbon is locked up in boreal and alpine permafrost, but estimates range from 350 to 450 gigatons—perhaps a quarter to a third of all soil carbon. The big question is what will happen if even a fraction of this massive carbon store is liberated.

Many parts of the Arctic are already

warming faster than any other region on Earth is, a trend that climate models predict will continue. Although researchers are struggling to arrive at a bottom line, they suspect that thawing permafrost will drive global temperatures higher over the next century. No one has a clue, though, how much higher. Thawing permafrost “is a real wild card in the carbon cycle,” says Lawson Brigham of the U.S. Arctic Research Commission in Fairbanks.

Cold storage
Any soil that stays frozen more than 2 years in a row counts as permafrost. The perpetual cold makes these soils an excellent carbon sink, because Arctic plants, such as sedges and mosses, decompose slowly after death. That results in living plants sucking from the atmosphere more carbon dioxide, the chief greenhouse gas, than is released from dead matter, building up thick organic soils. For tens of thousands of years, the far north has been accumulating carbon this way. In the upper reaches of Siberia, for example, peat deposits extend for thousands of kilometers and are hundreds of meters thick. Today, permafrost covers roughly a quarter of the land in the Northern Hemisphere.

Researchers first noticed a trend toward a widespread thaw after the U.S. Geological Survey started measuring rising temperatures in abandoned Arctic boreholes in the 1960s. It took another 2 decades to launch a concerted effort to probe how permafrost thawing—and the concomitant changes to overlying soils—might influence the amount of greenhouse gases released into the air.

One team, led by Walter Oechel, an ecologist at San Diego State University in California, started with the assumption that the Arctic was still a carbon sink. In the early 1980s, the researchers conducted experiments at Toolik Lake and Barrow, Alaska, where they measured gases wafting from tussocks and other typical High Arctic vegetation. To their amazement, they found that the Alaskan tundra was releasing more CO2 than it was absorbing. “This was contrary to all that was known about Arctic system functioning,” Oechel says.

The shift was primarily due to changes, brought on by warming, in how water moves through the soils. As Arctic soils warm, water seeps out of thawed permafrost and evaporates, often leaving the soils drier and more oxygenated. Under these conditions, microbes more readily break down dead plant matter, the bulk of organic material in Arctic soil. This decomposition releases CO2 into the atmosphere.

By 2000, however, the amount of CO2 escaping from the tundra had begun to taper off. Permafrost still appeared to be drying out, but woody shrubs and other plants that thrive in drier conditions were becoming more abundant—and absorbing CO2 from the air as they photosynthesized. “It was a total surprise that it was happening so quickly,” says Oechel. That observation has been backed up by aerial photos revealing the northern advance of shrubs over the past 3 decades.

Behind this trend are some complex phenomena. Thicker, colder deposits take longer to warm up. And vegetation can influence how much solar radiation reaches the soil: Trees reflect much less solar energy than do snow-covered sedges, for example. And denser vegetation is a better insulator of permafrost—leading to the counterintuitive situation of rising temperatures spurring plant growth and thus helping to preserve underlying permafrost.

Another key factor in determining the impact of thawing permafrost is topography. Where water can drain away easily, soils tend to release more CO2 and less methane. That’s because plant roots and some microbes exposed to oxygen will produce CO2, whereas methane-making microbes need a wet, oxygen-free environment. “That makes it hard to find a common pattern of CO2 and methane impact across the complex Arctic landscape,” says Oechel. “The hydrology is key, but it’s not well understood.”

In Manitoba, for example, the thawing of frozen wetlands has resulted in wetter soils and greater carbon uptake. Sphagnum mosses thrive in warm, wet bogs, and when they die, much more carbon is stored than in nearby permafrost-rich spruce forests, Camill reported in 2001. “The sheer act of just thawing out the permafrost is enough to double the peat accumulation,” he says, noting a similar pattern across western Canada. That implies a net CO2 uptake. It’s unclear, though, how warming is affecting Siberia’s prodigious peatlands, which have accumulated some 70 gigatons of carbon in the last 11,000 years (Science, 16 January, p. 353).

But CO2 is only part of the story. An ongoing study has documented that much of Sweden’s northern tundra has grown wetter over the past 3 decades, and it is giving off increasing amounts of methane—an even more powerful greenhouse gas than CO2. As the permafrost thaws, the tundra is changing into marshland, with permafrost having disappeared entirely from some of the new bogs. Thawed marshes release methane because standing water leaves them oxygen-deprived, prime conditions for bacteria that convert plant detritus into methane. (As noted above, bacteria that liberate CO2 thrive in aerobic conditions.) “We’re seeing dramatic changes,” says biogeochemist Torben Christensen of Lund University in Sweden. In one well-studied bog, he says, methane emissions appear to have risen by up to two-thirds since the early 1970s.

To chart the changes, Christensen and colleagues compared aerial photos of the Stordalen mire taken in 1970 and 2000. They tabulated four types of vegetation and checked the accuracy of the 2000 photo with a detailed field survey. The extent of drier plant communities, mainly mosses and shrubs, had declined from 9.2 to 5.9 hectares, the team reported in the 20 February issue of Geophysical Research Letters. Meanwhile, the abundance of sedges and other marshy plants increased by more than half. “The
thing that surprised me is the rate of change,” says Christensen. “Almost from year to year, we can see the vegetation changing.”

His team calculated that the shift in plants is correlated with a rise of between 22% and 66% in methane production by soil bacteria and plants. Methane measurements from the early 1970s at Stordalen back the increase. “It’s a pretty massive change,” notes William Reeburgh of the University of California, Irvine. Yet this may be a local phenomenon: Average regional temperatures in northern Sweden had hovered near freezing in recent decades, rendering the permafrost vulnerable to even a slight warming. Tundra in colder regions may not be so susceptible, Christensen notes.

All this uncertainty makes it difficult to predict the overall response of Arctic soils to global warming. Even basics are lacking, such as the precise extent of frozen peatlands. “So it’s difficult to calculate the gigatons of carbon they would release if they all thawed,” says Camill. Further complicating the forecast is the fact that few spots in the circumpolar north are studied well or at all—a point emphasized in a report on permafrost released this spring by the U.S. Arctic Research Commission (www.arctic.gov/files/PermafrostForWeb.pdf). That uncertainty makes any conclusion about carbon flux risky, says Christensen: “I would be hesitant to come up with any major statements saying the Arctic is a source or sink.” Still, he bets that even if the most northern, drier Arctic soils revert to being a carbon sink, methane emissions from thawed permafrost will likely accelerate global warming.

Some experts, however, predict that the methane will be accompanied by CO$_2$, and perhaps many gigatons could be released in the far north over the next century. “The Arctic is likely to be a huge positive feedback on global warming,” Oechel says, citing the fact that warmer, drier soil releases more CO$_2$, warmer, wetter soil releases more methane, and loss of snow and ice cover mean more solar rays warming the ground. Increasing rates of forest fires could also unleash large amounts of carbon. The greening of the Arctic may eventually absorb much of the carbon released from cold storage, he says. But several generations of people will still have to cope with what is shaping up to be a fearful loss of permanence.

—Erik Stokstad

**NEWS**

**The Secret Life of Fungi**

It all started with truffles. In the late 1880s, German foresters eager to grow these fungal delicacies asked a colleague, A. B. Frank, to figure out how they propagate. He undertook the quest and unearthed a hidden world in which truffles and other fungi work with plants to create a mutual support network underground. It has taken more than a century for Frank’s scientific descendants to make sense of the tangles of fungal threads and plant roots that he dug up, and what they’ve learned is changing the way people think about plant ecology.

The mycorrhizal species of fungi live hidden in the soil most of the time. They are probably best known for their fruiting structures—such as toadstools—that often pop up next to tree trunks. Less diverse but more pervasive are the arbuscular mycorrhizal fungi, which never see the light of day. Both types send out extensive networks of fine threads called mycelia, sometimes up to 20,000 km in 1 cubic meter of soil, which link with and extend the reach of plant roots. Because of their small size, one-sixtieth as thin as roots, the threads can get into tight spaces and retrieve hard-to-get nutrients. The fungi efficiently deliver soil minerals, particularly phosphorus and nitrogen; the plants reward them with energizing sugars.

Ecologists and physiologists are finding that mycorrhizae—the union of roots and these soil fungi—do more than enhance a plant’s nutritional status. By hindering water loss and erosion, they improve the soil. They also protect against pathogens and dampen harm from toxic wastes—talents that researchers exploit to reduce fertilizer use and remake damaged ecosystems. In addition, new studies are showing that these fungal threads link one plant to another, transferring nutrients not only among fungi but from plant to plant as well, shaping the biological makeup of whole communities. All in all, “I suspect that many plants would not be able to survive in nature without being aided by these small and unseen [partners],” says Marcel van der Heijden, an ecologist at the Free University Amsterdam, the Netherlands.

**The dirt on mycorrhizae**

Frank was among the first to realize that—in contrast to a widely held view—soil microorganisms aren’t always harmful. He demonstrated this by planting seeds in soil collected from pine forests, some of which had been sterilized, some left in its natural state. “Only in the natural soil did he get a big growth of plants,” says David Read, an ecologist at the University of Sheffield, U.K.

About the same time, other researchers were discovering that mycorrhizae were widespread: Boreal, temperate, alpine, and tropical forests all have them, as do grasslands and tundras. The few exceptions were lava fields, strip mines, and other places robbed of topsoil—or farmland that had been heavily fertilized. And many plants seem to benefit from these plant-fungi partnerships.

All told, biologists have found, the roots of about 80% of plants are entwined with mycorrhizal fungi. “It would be hard to go outside anywhere and pick up any handful of soil and not have mycorrhizae,” says John Klironomos, a soil ecologist at the University of Guelph in Ontario, Canada. They help plants settle into damaged areas, such as those destroyed by fire. And their role appears to be ancient. Four hundred million years ago, “when the first plants colonized land, mycorrhizal fungi were there,” helping...