Soil researchers setting out to work: New director Susan Trumbore (far right), group head Markus Reichstein (in the orange pullover) and his colleagues from the Max Planck Institute for Biogeochemistry set out to obtain soil samples for later analysis in the laboratory.

Photo: Sven Döring

Climate Buried **in the Soil**

The role of soil has been largely neglected in climate models to date, but this is set to change. Scientists working with **Markus Reichstein** at the **Max Planck Institute for Biogeochemistry** in Jena are studying the climate-relevant processes that take place below ground and are developing models to describe them.

TEXT **CORNELIA REICHERT**

The Earth is a living, self-regulating super-organism. When British geochemist James Lovelock presented this concept of the Earth in his Gaia theory in the 1970s, he attracted much praise and much criticism: theologians, esoterics and those seeking meaning welcomed the new holistic perspective. Science, however, rejected the theory and condemned, in particular, Lovelock's lax use of the concept "life" – after all, the Earth cannot reproduce. But with the intensification of climate research, it has become increasingly clear that the only approach that can work here is a systemic one – the idea of the Earth as a holistic system.

Researchers agree that polar ice, the oceans, the atmosphere and forests are the main protagonists of the global climate system. But what about the soil? It is largely ignored in the standard model calculations, such as those on which the current IPCC World Climate Report of 2007 is based. However, questions such as how the biogeochemical processes below ground react to the fact that the climate is changing and, conversely, how the processes below ground influence the climate must also be explored.

"As a factor in the Earth system, soil is the poor cousin when it comes to research, and we would like to remedy this," says Markus Reichstein, who heads a research group at the Max Planck Institute for Biogeochemistry in Jena. "I believe that soil has thus far been significantly underestimated as a climate factor."

"A RISING STAR IN THE FIELD OF ECOLOGY"

Since his student days, Markus Reichstein's main focus has been the world beneath his feet. He studied landscape ecology at the University of Münster and researched humus in the mountain soils of Davos, Switzerland for his degree. Today, he also seeks to understand the processes that take place below ground through theoretical approaches. Since 2006, the junior researcher and his team have been developing possible models for the role of soil in the climate system. >

Photo: Sven Döring

Their work is highly regarded throughout the world. For example, the journal SCIENCE WATCH from the Institute for Science Information (ISI) in Philadelphia regularly publishes statistics on who is leading the science race. On its website, Reichstein has been dubbed a "rising star in the field of environmental science and ecology."

THE TOOLS: MATHEMATICS AND A CORE SAMPLER

"The art of modeling consists in abstracting the real world and creating a link to the world of mathematical formulas," says Markus Reichstein. Mathematics is an important tool here, but no more than that: "I remember, for instance, a mathematician who started a doctorate at the same time as I did. He was excellent at his subject, but he had enormous difficulties in reconciling the real world with mathematics." To do this, the gap between the sciences must be bridged, and this is precisely what Reichstein and his colleagues do: they use field and laboratory experiments to test how well or poorly their theoretical hypotheses describe reality.

"To be able to even consider how the soil could be described in terms of mathematical formulas, one must first understand what the soil actually is and just what goes on within it," says Reichstein. The soil forms the intermediate world between the surface of the Earth's rocky crust on the one hand, and the vegetation cover and air on the other.

The soil comprises different layers, which experts call horizons. Below the top buffer layer lies the humus horizon, a layer of dead and decaying plant material. Beneath the humus lies the weathering layer, in which the minerals of the Earth's rocky crust are broken down and converted. Each individual layer is teeming with life: "Wherever you dig, you'll find billions of different microorganisms frolicking about in every handful of soil," says Reichstein.

The droves of bacteria, protozoa, fungi, algae, worms and insects live at different depths in the soil and in very different ways. Some of them enter into symbiosis with plants. Through their roots, the plants release carbohydrates, from which the microorganisms live. In turn, the microorganisms give nutrients back to the plants – a classic win-win situation: everyone gives, everyone takes, and everyone benefits. Some of the other tiny organisms live from plant mortality. Bacteria and protozoa, for example, get their energy by breaking up dead plant material, digesting it and consuming the carbon from it.

In this way, along with the far stronger greenhouse gases methane and nitrous oxide, an estimated 60 to 80 gigatons of carbon pour into the air annually in the form of carbon dioxide. At

left | For sampling, technician Marco Pöhlmann drives an extraction probe into the forest soil. Markus Reichstein, Susan Trumbore, Marion Schrumpf, and Enrico Weber (from left) await the core with interest.

above left | The core cutter provides a soil sample comprising several layers. Later, at the institute, the scientists will examine the composition of the soil from different depths.

above right | Life below ground: Each sample contains innumerable organisms that consume plant material, including earthworms. The latter's excrement, known as earthworm casts, is an important fertilizer.

the same time, humans propel 8 gigatons of carbon in the form of carbon dioxide into the air through the combustion of fossil fuels. "These figures alone demonstrate how significant soil might be for the carbon cycle and thus for the climate system," says Reichstein.

CLIMATE WARMING ALSO HEATS UP THE SOIL

Plants re-absorb the greenhouse gas carbon dioxide through photosynthesis. If the volume absorbed corresponds to that released by soil respiration, the system is in equilibrium and the carbon dioxide concentration in the atmosphere does not change. Some forest areas absorb more of the gas than they release. In total, the soil now contains over 3,000 gigatons of carbon: more than four times as much as the atmosphere.

In the future, however, the soil could release more of the climate-damaging gas than it absorbs, because global warming is also heating up the soil, and the metabolism of the organisms in it is increasing. As a result, the microorganisms will decompose more plant material in less time and exhale more carbon dioxide which, in turn, will further heat up the atmosphere. This could intensify the greenhouse gas effect.

Whether this will happen or whether the system will buffer itself is a matter of some dispute, and as regards concrete figures, the forecasts are imprecise at best. "Most models say that ecosystems will initially continue to absorb carbon," explains Reichstein. "Other prognoses, however, state that the system could swing in the opposite direction due to feedbacks." The soil would indeed then change from being a net carbon sink to a net carbon source.

An international team of scientists working with the French environmental researcher Pierre Friedlingstein carried out test calculations on 11 different carbon-cycle climate models and compared the results. The greatest cause for optimism is currently reflected in the forecast by the Lawrence Livermore National Laboratory in California, which states that the soil will continue to bind carbon dioxide, perhaps even more than it does at present. Another model from the University of Maryland suggests that the soil will behave the same way in the future as it does today.

The bleakest prognosis comes from the results of a model developed by the Hadley Centre in Great Britain. According to this forecast, the soil could release more than three gigatons of carbon annually by the year 2100. "That is probably very overstated, but it is entirely possible that the soil could become a climate heater," notes Max Planck researcher Reichstein.

Which scenario will actually take place depends on a tiny factor in a rule of thumb known as the Van 't Hoff rule. The Van 't Hoff rule describes the inter-

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action between the reaction rate of the soil as a function of temperature and, therefore, the climate effect triggered by the soil organisms. According to this rule of thumb, soil activity doubles when the temperature rises by 10 degrees. This rule, which is simple textbook knowledge, appeared to describe what happens in reality relatively well.

This was also the case in the context of science, at least thus far. “We now know that this factor dictates how things develop,” says Reichstein. “So it is essential that we establish exactly how high this factor is and whether it can change.” Will the soil activity double, or will it perhaps increase by a factor of just 1.5? Or will it perhaps even triple? This figure will determine whether the soil remains a carbon sink, becomes a more neutral climate factor, or heightens the greenhouse effect.

The uncertainty surrounding the precise level of the factor in the Van ’t Hoff rule is rooted in, among other things, a certain detail relating to biomass decomposition in the soil. The principle is undisputed: microbes metabolize dead material, they breathe out carbon dioxide, and the soil outgases. Other plants die, the microbes attack the fresh biomass and, at the same time, further break down older, pre-digested humus material. What soil scientists do not agree on is how quickly and to what extent the soil organisms break down the fresh biomass and the older material.

FRESH BIOMASS WHETS THE APPETITE FOR OLD FARE

Classic models describe what happens when the temperature increases as follows: Due to the effect of warming, the soil inhabitants eat up fresh biomass faster, but their appetite for the old material remains the same. As a result, soil respiration would increase, but the soil would ultimately remain a carbon sink. “This is precisely what we question. Soil microbes very much lead an independent existence. How they behave may not be quite as easy to predict as was thought,” says Markus Reichstein.

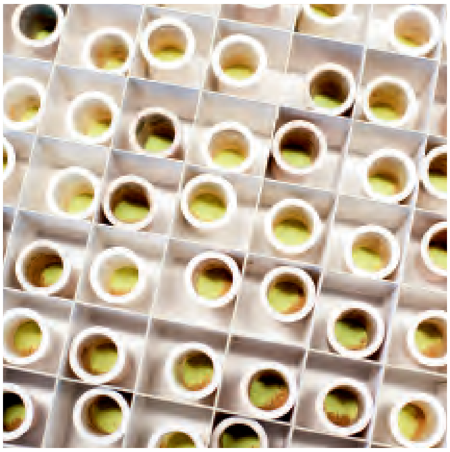
The researcher and his colleagues assume that the priming effect kicks in: “Whenever fresh new biomass is available to the microbes, their appetite for the old humus material increases.” The decomposition process accelerates and the soil emits more carbon dioxide. In addition, the microbes thrive and proliferate. “The warmer the soil becomes, the further the system is intensified,” explains Reichstein. Fresh biomass acts almost as an aperitif that stimulates the microorganisms’ appetite for older food.

However, some soil processes counteract the decomposition: chemical interactions between minerals hold the carbon in the soil at a constant level. Iron and aluminum hydroxides, for example, often accumulate carbon on their surfaces, from which it initially does not detach.

The researchers devised a number of possible mathematical formulas that can be programmed in a computer to calculate as simply as possible and with sufficient accuracy how these processes interact. They want to use laboratory and field experiments to determine which of these formulas is most suitable, so they must now shift their focus below ground.

Reichstein and his colleagues succeeded in attracting millions in funding for their project from the European

Photo: Sven Döring



above | To enable the measurement of their carbon and nitrogen content, the soil samples are ground and weighed in ceramic crucibles (left). The yellow color comes from tungsten oxide, which acts as a catalyst. An automatic sample dispenser assists in determining the total carbon content (center). The crucibles with the samples are heated to a temperature of 1,100 degrees Celsius for this purpose. The researchers examine the conversion processes in the soil in automated incubation experiments under controlled temperature and humidity conditions (right).

left | The work begins in earnest back in the laboratory: Markus Reichstein presents dozens of soil samples that are dried before being analyzed – here in a greenhouse due to lack of space.

Photos: Sven Döring

Research Council (ERC). As part of the QUASOM project (quantifying and modeling pathways of soil organic matter as affected by abiotic factors, microbial dynamics and transport processes), they aim to merge data from new field experiments with data from other European research projects in a soil simulation model.

Marion Schrumpf from the biogeochemical processes department brought valuable experience with field data to the team, having already collected field data as part of the Carbo-Europe project (Assessment of the European Terrestrial Carbon Balance). This project explored the question of how the activity in the soil changes over time throughout the continent, and how forests and arable areas can be managed so that their soils bind as much carbon dioxide as possible. Sixty-one research institutes from 17 European countries participated in this project, which was headed by the now retired Founding Director of the Max Planck Institute in Jena, Ernst-Detlef Schulze.

The researchers involved frequently broke new methodological ground. “A comprehensive soil inventory had simply never been carried out before,” reports Marion Schrumpf. The data available on forest soils, for example, is extremely sparse. “The forestry sector was interested in its tree population, but not in the soil on which they grow,” says the researcher. The little data available stems from agriculture. Farmers and agricultural scientists have been observing how arable soils react to different management practices for more than 100 years. These long time series of soil analyses can now be used to learn something about the effect of climate change on soil carbon. However, the agricultural data is often far from complete. “Besides, this work was carried out from an entirely different perspective,” says Schrumpf. Agriculture is interested primarily in information about soil fertility. The scientists working on Carbo-Europe and QUASOM, on the other hand, look at the soil from the perspective of climate research: high carbon content in the soil not only increases fertility and yields, but also means that carbon is being removed from the air.

As part of Carbo-Europe, Marion Schrumpf worked on core samples from 12 locations. The samples were taken in places that also had towers for atmospheric measurements. “As a result, we had a good supply not only of soil data, but of other environmental parameters as well,” says the researcher. She examined a total of more than 9,000 samples – an enormous undertaking.

IT IS NOT ENOUGH TO SIMPLY GO OUT AND DIG

It starts with sampling: “Life would be easy for us if the world were just a pile of sand,” says Schrumpf. “It isn’t enough to simply go out, dig a bit, and bring back a mound of soil, as people might think.” That is why she drives a core sampler into the subsoil. “That can be very strenuous,” says the researcher, as many soils are rock hard. And the deeper they penetrate, the more solid they become.

“Besides, you can’t simply put some soil into plastic bags to get samples,” says Schrumpf. “For quantitative tests, you have to remove a precisely defined volume of soil from the earth and know the depth from which the sample originates.” And because the scientists in this project are interested

Data analysis on the computer: Markus Reichstein analyzes the CO_2 flows from the soil into the incubation containers. The window provides a view into the climate chamber where Stefany Thiessen, a doctoral student working on the QUASOM project, monitors one of the 80 containers.

in how soil changes over time, they will have to sample the same places again in a few years.

UNDERWORLD PROCESSES IN THE LABORATORY

The sampling for the Carbo-Europe project has since been completed, but the analytical work continues in the laboratory. Schrumpf sorts the roots from the samples, dries them, sieves and grinds them, and then measures their carbon content: “It takes at least 45 minutes per sample, not including the drying time.” It is planned to examine some of the locations regularly in the future – ideally over a period of decades. Schrumpf and her colleagues will then repeat the entire procedure again.

The soil researchers will also be heading out regularly to collect samples for the QUASOM tests. As was the case with Carbo-Europe, the researchers will put the soil samples to work under controlled conditions in the lab. “We can control each factor individually – from the volume of fresh material added, to the temperature, humidity and wind conditions – and examine how a particular soil reacts under certain conditions,” says the head of the research group, Markus Reichstein. In this way, the scientists can track the individual processes that occur below ground and find out what happens and how under very specific conditions.

But laboratory experiments also have their limitations: they provide data about an artificial subsystem; the real conditions outside could be very different. The researchers thus also want to carry out additional tests in the field. The data obtained there may be less accurate, as it is more transitory due to the effect of wind and weather, but taken together, the field and laboratory values provide a solid knowledge base.

This is supplemented by values from the air, obtained as part of the Fluxnet project, a global network of carbon dioxide and water vapor measurements. Along with the vertical wind speed, the carbon dioxide and water concentrations in the air layer above ecosystems are determined 10 to 20 times per second. Reichstein and his team use these values to deduce the amount of the two substances exchanged between the soil system and the air. The great advantage of this type of measurement is that it does not influence or alter the ecosystem itself. The measurements can thus continue for many years without concern. Satellite data help transfer the information to larger areas, even entire continents.

All of the data collected by the project ends up in the computers of Thomas Wutzler and Christian Beer,

Photo: Sven Döring

the team's computer scientists. Wutzler analyzes the data statistically and feeds it into the previously formulated models. All of the models are theoretically coherent and consistent and therefore equally plausible. The formula that best conveys the reality as gleaned from the new data will eventually be incorporated into the global climate simulation. This is Beer's responsibility. His large-scale simulations combine the local, regional, national and continental studies to produce a comprehensive picture.

Reichstein's team is now also enjoying additional prominent scientific support in its attempt to clarify the role of soil in the global greenhouse: Susan Trumbore, Ernst-Detlef Schulze's successor, joined the Max Planck Institute for Biogeochemistry in September. As part of her previous research in America and Switzerland, Trumbore focused on, among other things, the question of how the potential of soils as future sources of carbon dioxide can be calculated. "We want to work closely together on this," Trumbore and Reichstein agree.

And much remains to be done. It is still far too early to obtain reliable soil forecasts – if possible for the whole world, and for centuries. It will be years before this stage is reached. "The soil holds some of the last secrets of the Earth system. We need to uncover these to be able to provide better and more reliable climate forecasts," says Reichstein. ◂

GLOSSARY

Priming effect
Certain substances, such as fresh biomass, can increase the general activity of microorganisms in the soil.

Carbo-Europe
A project aimed at understanding and quantifying Europe's terrestrial carbon balance.

Fluxnet
A global network of micrometeorological towers that measure the exchange of carbon dioxide, water vapor and energy between ecosystems and the atmosphere.

QUASOM
A project aimed at attaining a better understanding of the interaction between biological and physical-chemical processes in the soil.