A LONG DRY SUMMER

In parts of the world already facing unreliable food supplies, an uncertain climate adds to the future stress for soils, plants and people. **Quirin Schiermeier** reports on water strategies for a drier world.

The record-breaking European heatwave of 2003 did not come out of the blue. It was preceded by an unusually dry spring during which soils dried up across the continent. The lack of moisture resulted in strongly reduced soil evaporation and cooling, which in turn intensified the temperature extremes during the summer.

Climate scientists believe that in the second half of this century, extreme summer heat and drought could become the rule rather than the exception as global temperatures rise. In any case, rapid loss of soil moisture early in the year now seems to be a signal for subsequent summer heatwaves in Europe[1]. A feedback loop appears to be at work: as heat dries up the soil, the dry soil amplifies the heat.

Changes in soil moisture content may have other feedbacks, affecting soil erosion, surface runoff, soil nutrients and even cloud formation. But predictions of soil drying in response to rising temperatures are still very uncertain. For Africa and South America, climate modellers are not even confident about the sign of the simulated changes.

"We are told climate variability will increase and that it may get drier in some regions, but we really know too little about the details," says Malin Falkenmark, a hydrologist and water-management expert at the Stockholm International Water Institute in Sweden. This uncertainty hasn't stopped Falkenmark, along with other hydrologists, from recommending changes to water-management practices in response to climate change, and to declare an end to the wait-and-see approach of the past[2].

"We don't know for sure how climate change will unfold, but there's no doubt any more that it is happening and that there needs to be some preparedness," Falkenmark says. "River flow in some dry regions may decrease by up to 40%, for example. That must alter water-resource planning methods. We cannot just wait until it happens."

Current models suggest that more rain will fall, but less often, leading to longer periods during which soil moisture is critically depleted. Observations from several regions, including North America, Europe, southern Africa and Australia, confirm a trend towards heavier rainfall events, with longer dry periods in between, particularly during the summer[3].

Down to earth

Observable trends for soil moisture are more elusive. As yet, soils seem to be more resilient to global warming than, say, mountain glaciers or polar ice sheets. In the few regions where good records are available — such as the Ukraine, where scientists have measured soil moisture for 45 years — researchers have found no evidence for much of a downward trend, if any.

"Soil moisture is not an easily measured quantity," says Jerry Meehl, a climate researcher at the US National Center for Atmospheric Research in Boulder, Colorado, and a lead author for the Intergovernmental Panel on Climate Change (IPCC). "The IPCC first predicted increased mid-continental summer drying of soils almost 20 years ago," he notes. In the absence of observations to support or refute this prediction, the science has not advanced much since then.

Climate models are consistent in predicting greater summer soil dryness after 2050 in parts of every continent except Antarctica. But where that will change, and how much, depends heavily on the model (see maps, below), none of which are yet good enough to allow detailed soil moisture predictions at the river-basin scale or below — the scale that matters to water-management experts such as Falkenmark.

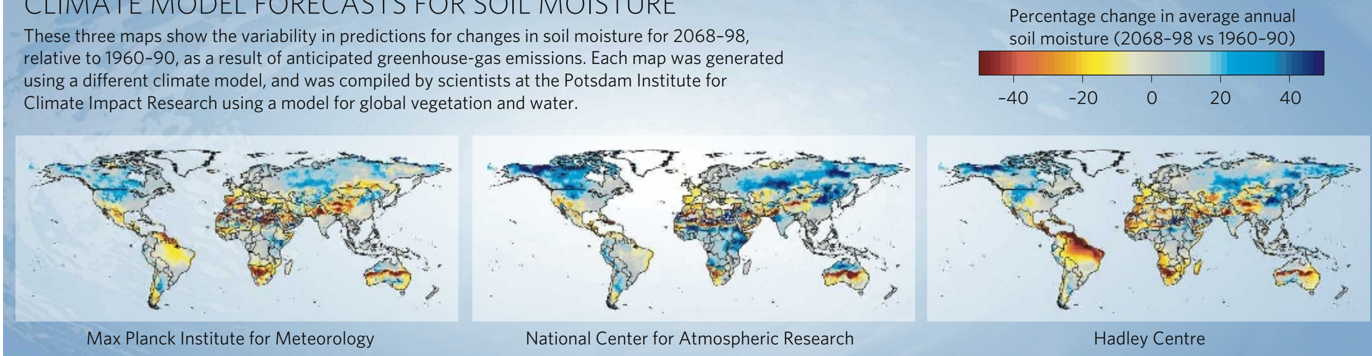
The main reason for the fuzziness is that it is much more difficult to model rainfall than temperature. The processes that control rainfall, such as cloud and droplet formation, occur on much smaller scales than are used by existing climate models. Soils are also too patchy to be reliably represented in current models. Finally, the complex interactions between rainfall, evaporation, carbon dioxide concentration, plant growth and soil moisture are not easily computerized.

Because soil moisture and rainfall influence each other, the models desperately need better soil data to improve. Yet the world's soils are not nearly as well monitored as temperature or precipitation; *in situ* observations are few and scattered. To disentangle the complex interplay, scientists would need to find some way to measure soil moisture content directly and continuously.

There is hope that satellite measurements will help. Both the European Space Agency (ESA) and NASA are planning missions to

CLIMATE MODEL FORECASTS FOR SOIL MOISTURE

These three maps show the variability in predictions for changes in soil moisture for 2068–98, relative to 1960–90, as a result of anticipated greenhouse-gas emissions. Each map was generated using a different climate model, and was compiled by scientists at the Potsdam Institute for Climate Impact Research using a model for global vegetation and water.



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observe soil moisture, expanding the work of ESA satellites ERS-1 and ERS-2. The microwave sensors on board the planned missions will give almost global coverage of soil moisture changes in real time. Where dense vegetation hides the soil, greenness can be used as a substitute.

At the same time, increasing computer power is allowing researchers to improve their models. There's still some way to go, admits Peter Cox, a climate modeller at the University of Exeter, UK. Current models are not yet fine-grained enough to model individual tropical storms, for example. But Cox says that some regional models are getting close.

"The trick is to use various sources of information and fuse them together so as to construct a global data set," says Cox. "As climate models and satellite observations are converging in scale and resolution, we can start ingesting satellite data into our models and make them more powerful."

> "In Africa, 'rainy season' means that rain can fall, not that it will fall."
> — Malin Falkenmark

The public usually associates water shortages with a lack of drinking water. But global water scarcity is primarily an issue of hunger, not thirst. Declining soil moisture generally means an increasing risk of drought. Monitoring and understanding possible soil moisture changes is therefore vital for crop management in all regions at risk of water scarcity.

Researchers expect the most severe impacts to occur in the transition zones between wet and dry climates. In very wet regions, where soil water is always plentiful, evaporation and precipitation are hardly sensitive to soil moisture. And in very dry regions the rate of evaporation is too small to generate much precipitation anyway.

In one of the best available estimates, a multi-model study conducted by the Global Land–Atmosphere Coupling Experiment, run by the World Climate Research Programme, the hot spots of coupling between soil moisture and precipitation appear in the plains of North America, sub-Saharan Africa and northern India[4]. These regions, and in particular the 'hunger belt' from the Sahel to the Horn of Africa, are thought to be most at risk from the effects of climate change, such as more frequent droughts and floods, and accelerated soil erosion.

Soils store rainfall in the root zone of plants. This is called 'green water', as opposed to the blue water in rivers, lakes and groundwater stores. In dry regions, blue water is usually very scarce, often accounting for less than 10% of the overall water balance. All rain-fed agriculture in tropical and savannah regions, where irrigation is minor, depends on soils' capacity to capture what little rain falls.

Feeling the heat: the frequency of droughts like that seen in Europe in 2003 is likely to increase.

"Green water is the key to water and food security in drought-prone regions," says Falkenmark, who coined the term in the early 1990s. But experts believe that only 10–30% of rainfall in the world's savannah belt — the dry to moderately wet zones on all continents — is being used in a productive way.

The effect of climate change on water scarcity in regions that lack food security is becoming evident. Given the degree of human interference with climate and water, Falkenmark and other international experts recently declared dead the idea that water planners need consider only natural variability (and not human influence) when managing water supplies[2]. What the developing world needs now is a second 'green revolution', aimed at increasing yields by improving green-water management, soil conservation efforts, and more efficient protection of crops from prolonged dry spells, she says.

Green and blue water are not separate resources, of course. Irrigation turns blue water into green (see graphic, overleaf). But in dry regions it is difficult to improve water availability through engineering works such as dams. "It is very unsatisfactory, therefore, that

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Keep it simple

The year 2000 was another dry one in Kenya. With little rain during most of the growing season, the president declared a state of emergency and called for international food aid to support the starving population.

But while crops failed across the country, some corn (maize) growers in the Machakos district southeast of Nairobi had bumper yields of up to 3 tonnes per hectare.

This was not luck. The farmers had built a few small dams upstream, and stored some water from a downpour early in the season. It was only enough to fill two small swimming pools, but it was enough to bridge the dry spell.

What the Kenyan government called a severe meteorological drought, was really just an agricultural drought, says Johan Rockström, a water-management expert at Stockholm University, Sweden. There was plenty of rain, but most of it fell in one downpour at the start of the rainy season.

Rockström and his team are helping farmers in Kenya, Ethiopia, Uganda and Tanzania make better use of soil and erratic rainfall. Collecting water from local runoff, for irrigation during dry spells, is one plan. They are also advising farmers to switch from ploughing to tilling.

In the past 20 years, tilling has transformed farming in Latin America. By lightly tilling the soil rather than turning it with a heavy plough, farmers avoid forming hard troughs that hinder rainwater from entering the soil and can increase soil erosion. And if soils are not turned, less of the organic material that holds water will be exposed and get lost to the air by oxidation. A welcome side effect, climate-wise, is that more carbon stays in the ground.

But many African farmers hesitate to abandon the plough and return to tilling. Ploughing, which was introduced during colonial times, keeps weeds down. Poor farmers also worry about investing in new technology and expensive fertilizers for fear of losing their investment through crop failure.

Experts believe that maximizing rainfall infiltration into the soil, alongside water harvesting for irrigation, is key to producing more food in rainfed agricultures. If it gained wider acceptance, tillage alone could vastly improve water availability in savannah regions, says Rockström.

Simple means of improving water storage in agricultural soils could quadruple yields of important crops, says Rockström. "Climate change doesn't make the task easier," he says. "But we're certainly not hopeless." **Q.S.**

most water engineers are still mainly thinking in blue-water terms," says Falkenmark.

To capture green water in dry African regions, farmers need to make sure that enough rain can infiltrate the soil after dry spells, for example by adopting more soil-friendly ploughing techniques, which have already increased yields in Latin America. And experts recommend that farmers harvest water from local runoff to use during dry spells in the growing season (see 'Keep it simple').

Going green

Even without climate change, rain in the savannah belt is erratic. In sub-Saharan Africa, for example, dry spells typically occur even in 'wet' years. "In Africa," says Falkenmark, "the term 'rainy season' means that rain can fall, not that it will fall."

For soil moisture and green water, the local frequency and intensity of rainfall are at least as important as the total amount of precipitation. Heavy rain cannot penetrate parched and crusted soils, and without efficient water and land-use management, researchers warn that more variable rainfall in vulnerable regions threatens to increase runoff, erosion, water stress on plants and flooding.

Models agree that global warming will amplify the entire hydrological cycle, from evaporation to precipitation to runoff[5]. Global precipitation over land may slightly increase, especially in some northern latitudes or tropical regions, with a greater fraction occurring during the heaviest events.

Markus Reichstein, a carbon-cycle expert at the Max Planck Institute for Biogeochemistry in Jena, Germany, has studied the consequences of more extreme rainfall on ecosystems. He says all levels and processes of the ecosystem are likely to be affected, from runoff to soil evaporation and nutrient availability. Changes will affect all climate zones, but some ecosystems may respond very differently to others, a 15-strong interdisciplinary team concludes in its as yet unpublished review.

This irrigation system in Tanzania captures runoff water to boost water supplies in dry periods.

R. KAUTSKY/AZOTE IMAGES

"Global water scarcity is primarily an issue of hunger, not thirst."

Plants' ability to adapt to changing water and nutrient availability might be crucial for their survival in a warming world. Ecologists think there are thresholds beyond which plants become stressed. But these vary between ecosystems, and so may plants' responses to climate change.

Soil water availability generally limits plant growth and photosynthesis. But nutrient availability in soils increases during dry spells, which suppress nutrient uptake by plants more severely than nutrient mineralization.

Still, in all semi-arid regions more extreme rainfall will increase stress on crops and vegetation, scientists believe[6]. Unfortunately, these are also densely populated regions with unreliable food production. In sub-Saharan Africa, longer dry spells will harm vegetation and, without supplementary irrigation, decrease yields.

A question of breeding

How best to adapt? The 2003 heatwave, which reduced yields in some European countries by more than 50%, shows that the rich world is not immune from the consequences of a warming climate, and from the need to adapt.

But climate change is without doubt a much bigger threat to food security in poorer regions.

Experts warn that poverty tends to entrench the deficiencies of rain-fed agricultures in developing countries. As poor farmers cannot afford to invest in their crops, foreign investment aid or cheap loans are vital.

A recent analysis of climate risks for crops in 12 regions with food insecurity shows that crops such as oilseed rape, corn (maize) and wheat in south Asia and southern Africa are most vulnerable. Agricultural investment and adaptation efforts should focus on these crops and regions, the authors suggest[7].

"We're seeing a massive challenge," says David Lobell, an agricultural ecologist at Stanford University in California and one of the authors of the study, who warns that plant breeding is under-resourced.

"We must urgently develop new crop varieties tolerant to heat and drought, and not just maize," he says. "And we need to work hard and very quickly on it. Don't forget it can take 15 years of development effort until a new variety is adopted by farmers."

But without prior investment in water and land management, crop-adaptation efforts will be less effective, says Deborah Bossio, director of research at the International Water Management Institute in Colombo, Sri Lanka, and a lead author for the International Assessment of

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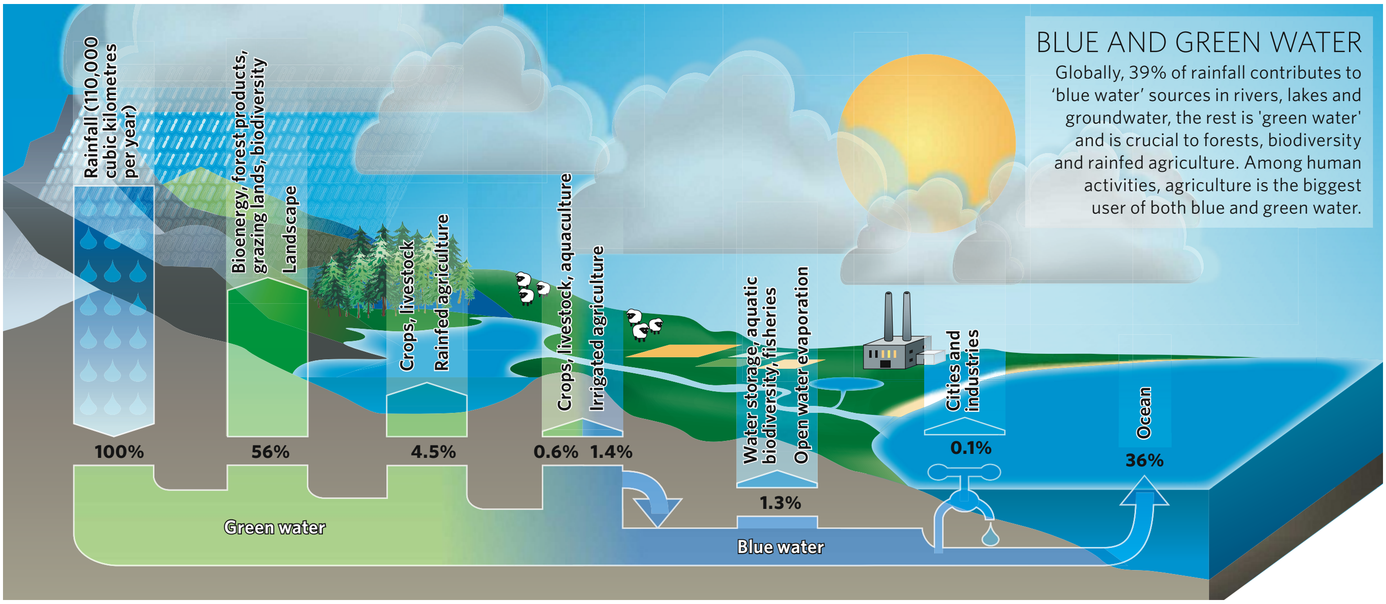

SOURCE: INTERNATIONAL WATER MANAGEMENT INSTITUTE

Agricultural Science and Technology Development, an international effort akin to the IPCC for agriculture.

Investment in water is particularly essential in south Asia and sub-Saharan Africa, says Bossio. And it should consider the full range of water storage and delivery options, she says, from the most local — soil water storage and farm ponds — to community projects such as small reservoirs.

But she warns that too much focus on crop production may put crops and livestock into conflict over water, with the risk that vulnerability is increased. "Livestock are always a very important component of the livelihood systems in areas at risk from water scarcity," says Bossio. Adaptation to water scarcity has to consider all the components that affect people's lives. ■

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See Editorial, page 253.
For more on water see www.nature.com/news/specials/water/index.html.

MORE CROP PER DROP

Farmers' yields in the developing world are often limited by unreliable rains. Improving their harvests will require plant breeders, agronomists and geneticists to pull together — but can these experts work out their differences? **Emma Marris** reports.

The International Assessment of Agricultural Science and Technology was to be to agriculture what the Intergovernmental Panel on Climate Change is to climate: the definitive statement of the scientific art. Hundreds of researchers have worked on the report for five years. It is co-sponsored by the United Nations, the Global Environmental Facility, the World Bank and the World Health Organization, and included in its vast pool of stakeholders are big companies, small farmers and scientists from around the world. But this January, CropLife International, the trade group that represents crop-science giants including Monsanto, DuPont and Syngenta, walked out.

At issue was the report's handling of the role of biotechnology in the developing world — or rather, the degree to which it chose to ignore that role. The crop-science companies think complex genetic traits will be a crucial part of the future of developing-world agriculture; the draft report, though, suggests that genetically modified (GM) crops have little to offer in this regard.

Because water (either from the sky or the irrigation canal) is often a key factor in determining crop yields, squeezing more crop out of the same drop (see 'Virtual water', page 275) will be central to one of the biggest challenges of this century: sustainably feeding a population of perhaps 9 billion people in a climate-changed world where rain, temperature and drought will be increasingly erratic. Already, 1.2 billion people live in areas where there is not enough water for everyone's needs[1] (see map, page 275), and that figure will probably grow faster than the overall population of the planet. Everyone agrees on the problem, but as the CropLife walkout demonstrated, not everyone agrees on the solution.

"Resources for GM development have been

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