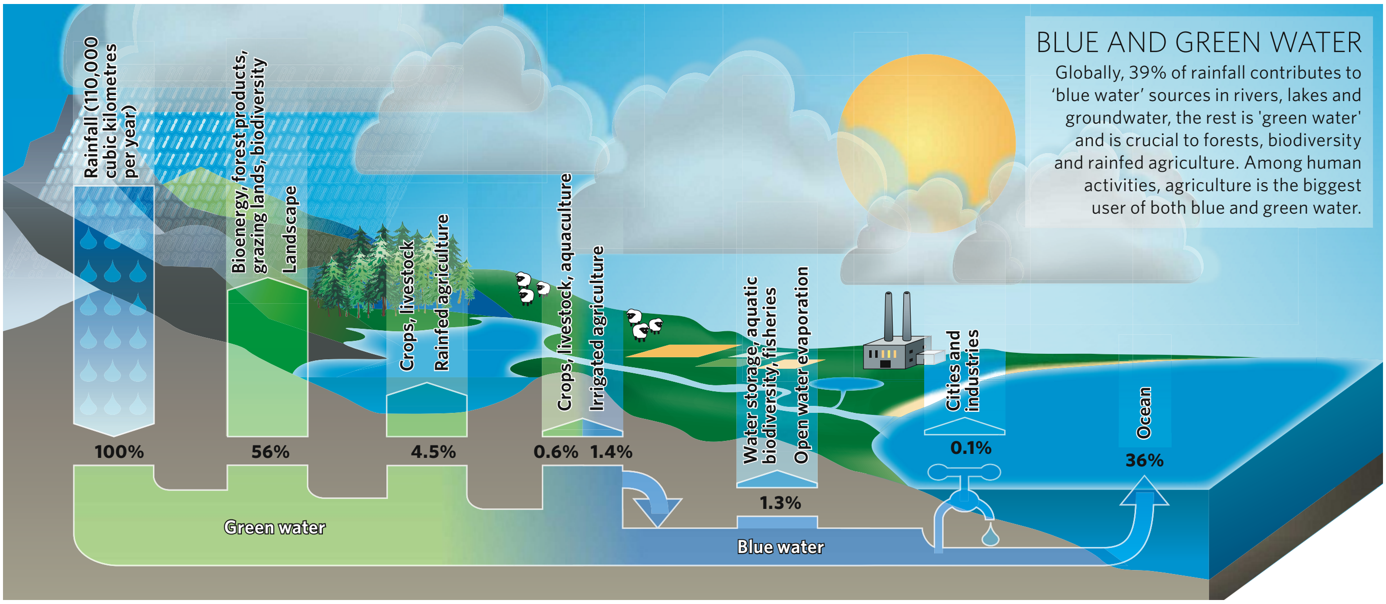

SOURCE: INTERNATIONAL WATER MANAGEMENT INSTITUTE

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. ■

Quirin Schiermeier is a reporter for *Nature* based in Munich.

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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

J. PIETRAGALLA/CIMMYT

spread very abundantly, with a great deal of overselling," cautions Pasquale Steduto, Italy-based chief of the United Nations Food and Agriculture Organization's Water, Development and Management Unit. "So far, we do not have a direct gain from GM or molecular biology in terms of drought resistance."

For Steduto, raising the maximum yield for a given crop with a given amount of water is not as useful as getting the many millions of low-yielding small farms up to where the efficient Western farms are now. For example, wheat, he says, seems to have an upper yield boundary of about 22 kilograms per hectare per millimetre of water per year. "The upper boundary is like an envelope, in which you see all sorts of productivity from almost zero to very close to this limit," he says. Agronomic techniques can be used to fill the envelope worldwide.

Yielding to technology

A recent report from the International Water Management Institute, one of the groups within the Consultative Group on International Agricultural Research, makes a similar point this way: "Seventy-five per cent of the additional food we need over the next decades could be met by bringing the production levels of the world's low-yield farmers up to 80% of what high-yield farmers get from comparable land." That is, land with similar soil and rainfall patterns. For example, says David Morden, the report's lead author, "grain yields in Uganda are on the order of 1 to 2 tonnes per hectare, and in a similar environment, one could expect 6 to 8 tonnes with really good management."

Much of the difference, the report says, can be made up by disseminating basic research techniques such as choosing a wise mix of crops and livestock for each plot or creating small dams or terraces for water management. Often, real gains are within an individual farmer's reach economically, if only they knew what they were. In other cases, increasing yields requires modest investments in technologies or inputs that could be provided by micro-investment or donations. And finally, better management at the country and international level will make for stronger markets and more reliable water supply (see 'Wilting watersheds', page 277).

Many in the world of agronomy and rural development see little role for biotechnology in these efforts. Despite vigorous adoption rates in the developed world — 60% of biotech crops are grown in developed countries[2] — it is conventional wisdom that biotechnology is at best a mixed blessing for the developing world. Some of this dismissal could reflect scepticism about the motives of seed companies. But those who work with genes say that they view it as impatience and a lack of faith in technology that is taking time to mature.

That's because the first GM crops were simple and came easy, says Marc van Montagu, a researcher at Ghent University in Belgium. He revolutionized agricultural biotechnology with the *Agrobacterium* method of introducing new genes into plants. But the game has moved on, and traits far more complicated than pesticide resistance are tougher to crack. "Drought tolerance looks dramatically complicated, but it can be done," van Montagu says. And it can be done only with biotechnology, he insists, "The best of traditional breeding is too slow."

> "Rocks and stones are drought tolerant, but plants need water. It is quite limited how much you can tune that." — Matthew Reynolds

Roger Beachy, head of the non-profit Donald Danforth Plant Science Center in St Louis, Missouri (partly funded by biotech giant Monsanto, across the street), admits that scientists promised too much too early in the field of drought tolerance. "There were some remarkable and extravagant predictions back in the 1980s," he says. "It comes back to haunt you." He compares the early buzz on genes associated with drought tolerance to the discovery of the first gene associated with breast cancer — *BRCA1*. People celebrated an imminent end to the disease, "and then they found a second and a third and a fourth and a fifth gene, and they realized it was more complicated".

This impatience is certainly felt by traditional plant breeders such as Marianne Bänziger at the Mexico-based International Maize and Wheat Improvement Center (CIMMYT). "At the moment there are probably hundreds of groups that work on transgenic drought tolerance," she says, "but very few have made it into the field and shown yield increases." She's also worried that transgenic approaches steal limelight — and funding — from traditional plant breeding, which is itself becoming much more powerful with the help of new genetic techniques that can speed up field-based breeding. Marker-assisted selection, for example, allows plant breeders to follow genetic markers linked to specific genes of interest.

In the long run, biotech researchers say, impatience is counterproductive. Beachy thinks the backlash against biotechnology is a grave mistake. "We are still in the infancy of advanced agriculture," he says, "and in the infant stages everyone thinks that their piece is more important than the next. As the world begins to recognize the severity of the problem, we will all become more collegial — we need everyone on board with all the tools in the arsenal."

Plants need water in all sorts of ways; without

A wheat researcher in Mexico measures crop temperature using an infrared sensor to estimate root depth during drought stress.

Virtual water

The goal of 'more crop per drop' can be tackled on several levels — the individual plant, the whole field, the whole river basin or the whole Earth. But efficiency gains on one level don't always improve the situation on the other levels. An arid country may find that it is more cost effective to give up producing commodities that require lots of water and buy them from abroad.

For example, a kilogram of modern industrial beef, according to Arjen Hoekstra, a water-management specialist at the University of Twente in the Netherlands, takes 15,500 litres of water to produce. So, rather than import all that water, why not instead import beef and concentrate your energies on an industry better suited to a dry country?

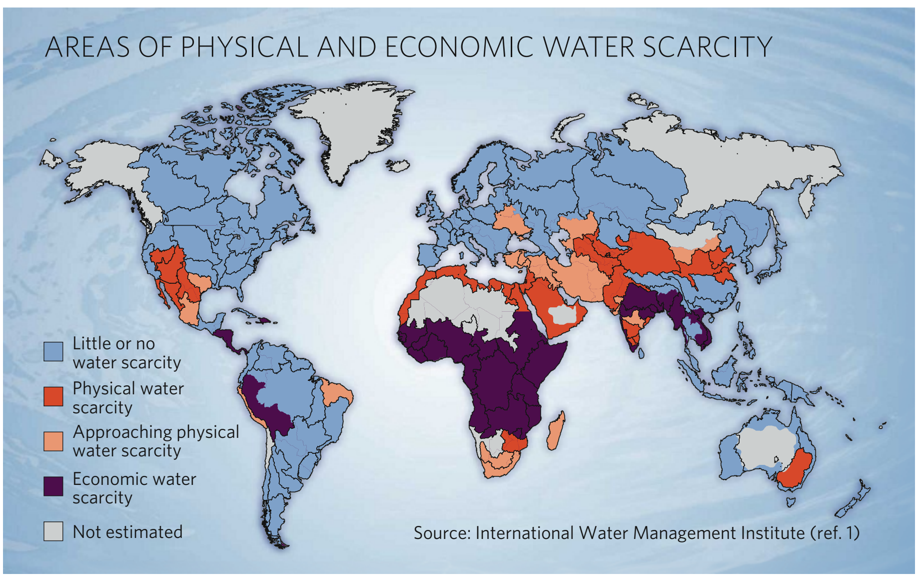
So far, just a few countries have taken the 'virtual water' idea on and folded it into their policies. Jordan stands out, consciously trying to increase its imports of water-intensive food. Policies such as these go against the grain in many countries, where self-sufficiency is often prized. But, as one might expect, some countries, such as China, that have increasingly felt the pinch of water scarcity have been "unconsciously" turning to virtual water imports[6].

Virtual-water researchers think big, in cubic kilometres of water. So do the possible genetic gains at the plant level even make it into their equations? "I see it as one of the many ways to try to reduce water needs," says Hoekstra. "Sometimes, in some cases, it can be a partial solution." **E.M.**

it they can't absorb nutrients or photosynthesize — and water pressure keeps green plants from wilting. To think plants can be made drought-proof is a mistake, says Matthew Reynolds, a wheat physiologist at CIMMYT. "Rocks and stones are drought tolerant, but plants need water. It is quite limited how much you can tune that."

What's more, the ways that plants deal with water stress when left to their own evolutionary devices may not suit the needs of farmers. One example is seed abortion in corn (maize). "Under drought conditions," says Bänziger, CIMMYT's director for corn research, "the maize plant puts more resources into pollen formation and less into seeds." From the plant's point of view this makes sense. Pollen is much cheaper energy-wise for the plant to make, and, if the pollen manages to fertilize another plant's seed, the drought-afflicted parent will still contribute 50% of its genes to the offspring. But this is of little help to farmers, who sell kernels, not pollen.

So one option is to stop the plants from doing what comes naturally during drought. "Plants normally avoid stress," says Eduardo Blumwald, a plant biologist at the University of California, Davis. "Actually we all avoid stress. If it is very dry, we go to the pub and have a beer." Tobacco plants close their stomata — the pores through which water is lost — and start shedding older leaves to reduce the area that transpires. "That strategy has worked for millions of years," says Blumwald, "it is a good strategy."



On a farm, though, it means that a lot of proteins and sugars that could end up in seeds are shed. So Blumwald engineered tobacco plants to retain a plant hormone called cytokinin in older leaves, so although they drooped, they weren't shed. When these modified plants are rewatered, the old leaves spring back, and the goodies inside them are available for seed growth[3]. "We find no cost; there is no yield penalty," says Blumwald, who says that one of the most common side effects of tweaking genes is a drop in yield.

Blumwald's work is still in model plants such as tobacco, however. Bänziger notes that a lot of transgenic research is done on another model plant, thale cress (*Arabidopsis thaliana*). She also worries that getting from lab to farm is hard and under-resourced. Even when research is done in field crops, she says, "it never gets past the lab bench because the environment in the field is very different".

And it is with traditional selective breeding, not GM techniques, that Reynolds and colleagues have developed several promising varieties of wheat that have higher yields in drought conditions, some of which are within a year or two of distribution. Some are crosses between modern lines and wild relatives of wheat from the Middle East, where the crop originated. These lines change their root architecture in drought conditions, going deeper.

Others take advantage of an accidental 500-year breeding experiment. Wheat came to Mexico with the conquistadors so that they could make bread for Catholic mass, Reynolds says, as "maize was considered a pagan crop". In the half-millennium since, farmers have adapted it to the dry local conditions. Many of

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"Resources for GM were spread very abundantly, with a great deal of overselling."
— Pasquale Steduto

these strains have very deep roots[4].

Often the same targets lend themselves to both breeding and biotech approaches. Some research avenues involve closing down stomata, others aim to pump up the water conductance of the whole plant or adjust leaf architecture to maximize photosynthesis even in wilting heat. Various techniques to make plants use carbon dioxide more efficiently — and thus keep their stomata more tightly shut — are under discussion. Such carbon dioxide concentration mechanisms have evolved naturally in various plant families.

Like many large seed companies, Pioneer Hi-Bred based in Johnston, Iowa, a business owned by chemicals giant DuPont, is working on both transgenic and traditional ways to extend the photosynthesis of a plant under drought stress, ways to dodge the dreaded seed abortion and ways to jiggle the plant's schedule around the calendar to keep its vulnerable flowering season out of the hottest weeks.

All these approaches begin with what is known about how plants deal with drought stress, and traditional breeding can't really jump off from anywhere else. But there are those who take a purely genetic approach to tweaking a plant's relationship with water. This includes mining plant genomes for any genes that seem to have something to do with drought response, and then tinkering with them. "It is really about characterizing the function of genes, genome-wide," says Jacqueline Heard, Monsanto's project leader for drought-tolerant corn.

Using a brute-force approach, Monsanto and Mendel Biotechnology of Hayward, California, are systematically investigating the transcription factors in the crops they work with, knocking them out or over-expressing them to see what they get. Transcription factors are genes that turn other genes on or off, and so they tend to be higher up in the cascade of changes that might unfold when a plant experiences stress. Monsanto and Mendel have found some promising contenders in model plants[5], and Monsanto has two drought-tolerant corn products in development, for delivery around 2015, that sprang from this approach.

"Our first products were all about weeds and bugs; we really believe that the next decade is going to be about yield," says Steve Padgette, Monsanto's vice-president for biotechnology research. He adds that although drought tolerance is indubitably more complex than the traits the industry has worked with before, research is catching up with the complexity. "The science is more tractable and the market is pulling," he says. William Niebur, vice-president for Crop Genetics Research and Development at Pioneer Hi-Bred, says that the company sees a market for drought-tolerant crops across all regions and at all scales, but the products, and the profits, may be long in coming. "This is much more complex than identifying a protein that will kill an insect or make a plant withstand a herbicide," says Niebur. "We see this as an area where we will spend our entire careers and there will still be room for improvement."

Down on the farm

Thanks to the constellations of funders and companies, it is nearly impossible to get global statistics that would show whether transgenics or agronomy is getting more money.

"I would guess that more money is put into genetic manipulation," says Reynolds, because "it is a lot easier to get a return on your investment. It is hard to patent an agronomic manipulation." And this, he thinks, is "positively dangerous. If we don't take care of the soil with the right agronomic strategies, then all our genetic manipulation will be futile."

This is why the world needs farm-level agronomists, detail-oriented and muddy-booted. Among them is Hubert Savenije, a hydrologist at the Delft University of Technology who has helped some Tanzanian farmers manage their farms better. "The biggest gains we can make are clearly when the rain infiltrates the soil," he says.

In his study areas in Tanzania, farmers practise a kind of specialized terracing called *fanya juu*, in which a series of trenches are dug perpendicular to the land's slope with soil heaped on their upslope sides. As water runs down, the heaps catch water for the plants immediately

OREGON STATE UNIV.

"We need everyone on board with all the tools in the arsenal."
— Roger Beachy

behind them. After several years of cultivation, such land looks like a series of lipped steps. Another technique is to cut the soil with a knife and plant corn seed in a 50-centimetre-deep slit, so that it roots deeply. And some farmers gather small amounts of water draining off fallow land, or a road. Increasing root depth, reducing evaporation of water from the soil and scavenging water to add back to soil are not new concepts to developing-world agronomy. But doing it right is difficult. "Every case is very specific and you have to experiment from a lot of options," says Savenije.

Iddi Murindaka, a farmer Savenije works with near Mwembe in Tanzania, uses *fanya juu*, spreads manure and diverts some water from a nearby gulley onto his crops. He remembers the last bad drought well. "We had no food; our livestock died; my family was in very poor health," he recalls. "We would sell two goats to buy 20 kilograms of maize." Now things have improved; his household boasts a recently purchased sewing machine and his children are able to attend school.

He and the other farmers Savenjie works with are interested in crop varieties that would mature early, beating the droughts, and thus make the most of their new farming practices. When asked which approach was more important, they all say "both". "Even with proper farm management, a poor seed will take longer," says Murindaka.

Tanzanian farmers want crop varieties that mature early to beat the drought as well as good agronomics.

R. KAUTSKY/AZOTE IMAGES

But that does not mean he would invest in a better seed, even if available, because the climate makes farmers risk-averse. "To this day we are not sure if it will rain or not the next season, so one's harvest is never secure," Walter Godfrey Mjema, another farmer working with Savenije, agrees. "You can say 'next season I will plant maize, and with the new farm management knowledge I will get a better yield, and with this I will buy some new household items,' but then it simply doesn't rain."

Despite the worries that sexy biotechnology is getting all the cash at the expense of researchers such as Savenije, interest in agronomy is growing. Both traditional funders and new donors, such as the Bill & Melinda Gates Foundation and Rockefeller Foundation joint venture, the Alliance for a Green Revolution, are now urging the importance of funding agricultural technologies.

According to the UK Overseas Development Institute, government funding of agriculture in developing countries fell by almost half, in real terms, between 1980 and 2005 whereas for overall development it was increasing 250%. But despite these decades of neglect, moves to fund agricultural technologies would be welcome indeed. Namanga Ngongi, president of the Alliance for a Green Revolution, says that they are looking into technologies such as foot-operated water pumps and solar-powered drip irrigation. And Rajiv Shah, director of agricultural development at the Gates Foundation, says they are eyeing management projects "at the farm and watershed level" as well as grants for traditional breeding.

"There is a huge interplay between crop genetics and crop management, and we believe that these approaches are complementary and synergistic," says Shah. "We are still formulating our priorities for these areas." Maybe agronomy and biotechnology will play nice and work together after all, if the donors push for it. ■

Emma Marris is a correspondent for *Nature* in Missouri.

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See Editorial, page 253.

For more on water see www.nature.com/news/specials/water/index.html

Wilting watersheds

Call them basins, catchments or watersheds, they are the level at which people have to share water day to day. In many basins, demand is tight. Farmers upstream and downstream are negotiating over who takes what out of the river or the groundwater, and they are often up against cities and industry. And there are the fish.

Examples of conflict-ridden basins are ubiquitous. In the United States, for example, the waters of the Colorado River in the south-west are in such hot demand by farmers and cities such as Phoenix that the fight between states, Native tribes and border countries for water rights has rumbled on since 1900.

Suppose a community is very proud that they have ceased over-watering their crops or lined their irrigation channels with plastic. Now imagine that the conserved water formerly sank into the soil and filled wells downslope. Basin-wide, you have no increased efficiency, and downstream you now have hopping-mad well owners.

Many closed basins, such as the Colorado (pictured) and China's Yellow River, no longer flow to the sea. The delta wetlands that once formed their mouths have become empty triangles. The Amu Darya and Syr Darya in Uzbekistan no longer make it to the Aral Sea, which is now half its former size, leaving boats stranded miles from the new shore.

Rivers with no or low flow can be ecological disasters. Scientists are just beginning to determine the minimum water that has to remain for the ecosystem to remain healthy. Fish will need a certain volume of water to swim up to mate, for example. The environment then becomes another competing consumer of water. "The environment is a resource, but it is also a user," says Vladimir Smakhtin, a principal hydrologist at the International Water Management Institute in Colombo, Sri Lanka. "It deserves a fair share of water." **E.M.**

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