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News Feature

Climate: Counting carbon in the Amazon

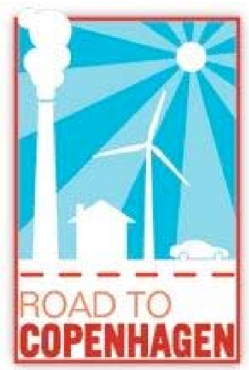
If the next climate treaty tackles deforestation, tropical nations will need to monitor the biomass of their forests. One ecologist has worked out a way to do that from the sky, finds Jeff Tollefson.

Jeff Tollefson

Greg Asner peers out an open window, taking stock of the jungle as the single-engine prop plane chugs over a pair of scarlet macaws gliding among the treetops 120 metres below. The Peruvian Amazon stretches in all directions, painted in countless shades of green, accented here and there by patches of purple, pink and yellow. Occasionally, naked white trunks rise amid the leaves, a reminder that even the rainforest has deciduous tendencies.

Forty-five minutes into the flight, Asner spots his quarry: narrow red trails, barely visible, then a fallen tree in the middle of an otherwise intact canopy. The cause isn't immediately clear to the untrained eye, but Asner knows all too well. "When trees die in the tropics, they don't just fall over," he says as the plane passes over more downed trees, a road, then a small clearing that contains stacked logs and a bulldozer. It is a legal concession, authorized by the Peruvian government to extract just three species of hardwood trees. As the plane veers away from the clearing, Asner gives his verdict. "The biomass levels are going to be a lot lower here," he says, "but it really is low-impact logging compared with the mayhem of Brazil."

As a tropical ecologist with the Carnegie Institution for Science's global ecology department in Stanford, California, Asner has developed a keen ability to interpret the rainforest from great heights. Frequently operating with oxygen masks at high altitude, his team uses a powerful laser system to map trees and calculate the biomass of the forest. Satellites extend his view across the tropics, and he has developed automated software that can track annual changes in forest cover and calculate the biomass of the vegetation. The system can even spot small logging operations like the one he just passed, which escape detection in most satellite studies.



Online collection G. ASNER

The fully integrated system is designed to measure the amount of carbon locked up in forests and to track changes over time — an exercise that may become a crucial foundation of the new climate treaty that global leaders are hoping to sign at the United Nations Climate Change Conference in Copenhagen this December. Tropical deforestation accounts for up to 20% of the carbon dioxide emitted by humanity each year and there is broad agreement on the need to include a forest-protection element in the new treaty. This component — known as REDD, for Reducing Emissions from Deforestation and Forest Degradation — would allow developed nations to meet their required emissions-reduction targets in part by paying tropical countries to preserve their forests, which keeps carbon in trees and out of the atmosphere.

But first, tropical nations must determine how much carbon is in the forest, a notoriously difficult task. A leading researcher on remote sensing in the tropics, Asner is out to prove that developing countries can quickly and cheaply perform their own analyses, then move on to long-term carbon monitoring. He has come to Peru to demonstrate the technology and he will present the results of this proof-of-concept test at a REDD meeting he is planning to coincide with the negotiations in Copenhagen. Success in Peru, he hopes, will bolster efforts to include a strong forest carbon component in the agreement.

The European Union last year called for a halving of deforestation by 2020, a goal that has since picked up political momentum. Estimates range widely, but reaching that target could mean pumping some US$20 billion into tropical countries each year, according to the Union of Concerned Scientists in Cambridge, Massachusetts. Venture capitalists see profits in forest carbon and have approached Asner with business offers. Instead he has licensed his technology, dubbed CLASLite, for Carnegie Landsat Analysis System Lite, and is providing it for free to governments and others. Starting in Latin America, his team is training scientists, officials and advocacy groups on how to use the software. He likes to say that he is putting himself and other scientists out of business by injecting a decade's worth of work into the public sphere.

All this effort in testing and training has meant devoting less time to academic research, but Asner says that his work on REDD has been nothing short of rejuvenating. "This is more fun than anything I've ever done as a scientist," he says. "These forests are really special. We need to get these people some cash and protect them."

Sweeping the forest

For Asner's crew in Peru, work starts early each morning. Today, a three-man team heads to a small airport in the southeastern part of the country before sunrise in an effort to get as much mapping done as possible before the jungle pumps enough water into the air to form midday clouds. Ty Kennedy-Bowdoin runs the Light Detection and Ranging system, or LIDAR, which sweeps a laser back and forth, blasting the forest with 70,000 laser pulses per second. A sensor continuously records the signals as they bounce off leaves, branches and other objects. These data enable the researchers to calculate the height, structure and density of the forest, and they use this information to determine how much biomass it holds.


Laser readings combined with other data yield a three-dimensional colour image.G. ASNER

Beside Kennedy-Bowdoin in the plane is James Jacobson, who monitors a hyperspectral imager that takes pictures using frequencies of light that range from the visible into the infrared. The spectral data are used mostly for research on forest biodiversity, although they can also be combined with the LIDAR data to create full-colour three-dimensional images. On this particular flight, Kennedy-Bowdoin eyes a computer monitor to confirm that the LIDAR readings are coming in properly as the plane slowly flies back and forth. But after several passes small clouds move in and block the laser. The plane returns to the airport, allowing the crew to break for lunch before another run in the evening, once the clouds have dissipated.

Back on the ground, Asner and a few colleagues head off into the jungle. They drive west along the InterOceanic Highway that crosses South America, then take a small logging road into the rainforest. It's dark by the time they finish a final hike to the Tambopata River and hop on a motor boat for a 45-minute ride to a research station upstream; a spotter scans the river with a flashlight, occasionally directing the boat away from logs.

There they meet up with a second team that is organizing ground plots. After waking up to the sound of monkeys in the morning, the team divides into several groups and heads out into the field; they have to finish around 30 plots before moving on to other locations throughout a study area larger than Denmark.


Greg Asner is trying to help tropical countries keep their forests intact.J. TOLLEFSON

At one of the field plots, strings stretch 30 metres out from a pole in multiple directions. In the middle, the researchers are busy running a tape measure around any tree bigger than 10 centimetres in diameter; in some places, they sample down to 5 centimetres. A laser finder gauges the height of each tree. With those data, Asner's team can calculate biomass for every tree in the plot, and those numbers are then plugged into equations to calculate the biomass for the patch of forest.

With a smile, Asner explains that this cumbersome process is currently the gold standard for biomass assessment. "People running tape measures around trees. This is what we've got to get away from," he says.


The CLASLite software developed by Greg Asner reveals where new forest destruction (green and yellow specks) extends into a protected area (red).J. TOLLEFSON/G. ASNER

Asner does this by taking to the skies. The laser pulses of the airborne LIDAR provide the main biomass estimate for large swathes of forest. The ground plots help his team to interpret and verify the laser readings for different types of vegetation (see 'How to measure a forest'). Old-growth forest filled with hardwood, for example, contains much more biomass per hectare than do regions dominated by bamboo. The CLASLite system then adds the numbers up according to vegetation type and extent to produce an estimate for the entire forest. Initial results suggest that these remote-sensing techniques are just as accurate as plots, Asner says, but they allow a small team to cover vast territories in a short time.

"Greg has already demonstrated that a tiny group of people can deploy this system over the scale of an entire country; the preliminary activities in Peru make that clear," says Chris Field, Asner's boss at Carnegie who is co-chair of the impacts, adaptation and vulnerability working group for the Intergovernmental Panel on Climate Change (IPCC). "I think it's an incredibly important development in science, and I'm a tremendous fan of his ability to make these things happen."

“The forces against deforestation are getting stronger, but the forces driving deforestation are getting stronger too.”
George Powell

Sandra Brown, a leading biomass expert at the non-profit organization Winrock International in Arlington, Virginia, acknowledges that plot-based assessments, although reliable, simply cannot cover as much territory as remote-sensing methods. She also says that published biomass estimates vary wildly for a given region, highlighting the need to establish baselines across the tropics that everybody can agree on. Stopping short of a blanket endorsement, she says that she is encouraged by Asner's initial results and is anxious to see the process in action. "I think it's got a lot of promise," she says.

The current project in Peru costs around $430,000, half of which was funded by the Norwegian government through a grant to the environmental group WWF. That equates to roughly 10 cents per hectare, with about half of the money spent on fuel and the plane, but Asner expects the costs to fall over time. Countries could elect to develop their own LIDAR capacity, he says, or hire one of the more than 100 commercial operators around the world. For perspective, Asner estimates that he could map all of the world's tropical forests with his system for roughly $15 million–$20 million.

Map quest

Asner owes his interest in forests to a hurricane named Iniki, which swept the Hawaiian islands in 1992. Asner was stationed there with the US Navy at the time, and he wound up surveying forest damage on Kaua'i after taking a job with the Nature Conservancy the following year. Asner recalls being "enthralled with the beauty, the wildness, the enormous hurricane damage and the onslaught of invasive species". His first scientific paper focused on the carnage caused by Iniki, but it was his work with invasive species that made him realize he was missing something as he struggled to assess the forest: maps.

“People running tape measures around trees. This is what we've got to get away from.”
Greg Asner

His quest for spatial data took him to the University of Colorado at Boulder for graduate work in ecology, biogeochemistry and remote sensing, and then all over the world. For Asner, now 41, it is hard to separate research from the rest of his life. His wife, Robin Martin, is a postdoc in his lab and they spend most of their time together in the field. And for the first test of the new biomass system earlier this year, he chose to measure Hawai'i, where he lives part time.

In that analysis, Asner's group identified roughly 48 million tonnes of above-ground biomass across the island. That is about 40% lower than the results the researchers obtained from published data and a simple protocol established by the IPCC, which would be the probable starting point for any country that is setting up a carbon-assessment programme. Asner's method has cut the calculated uncertainty in half and he says his system is accurate enough to meet criteria set out by the IPCC for advanced biomass monitoring (G. P. Asner Environ. Res. Lett. **4,** 034009; 2009). Satisfied with his results in Hawaii, Asner set his sights on Peru, where he has worked for several years on estimating biomass and other research.

The Carnegie crew began its project in Peru with a CLASLite analysis of NASA Landsat images around Puerto Maldonado, which is tucked into a corner of the southeastern Peruvian Amazon near Bolivia and Brazil (see map). Puerto is a poor frontier town of nearly 30,000 inhabitants, with more descending from the Andes along the newly paved InterOceanic Highway every day in pursuit of riches provided by logging, agriculture and, most recently, gold mining. Rainforest is nowhere to be seen in this dusty Amazonian town, but thousands of motorcycles buzz about, many powering a local variation on the rickshaw taxi.

The region around Puerto Maldonado, however, is one of the most biodiverse locations on the planet and a hub of deforestation. This makes it a prime target for Asner, who says that the government has shown it is ready to protect its forests.

In 2008, Peru created its first environment ministry. Vanessa Vereau, former vice-minister, says that Peru is working to build up regional governance even as it increases federal enforcement capacity by putting more police on the ground. It is also installing federal prosecutors in rural areas to ensure that everybody — government officials, companies and individuals — face real consequences when they break environmental laws. Success is by no means assured, but the government has not even tried to impose such order until now, says Vereau. Peru has also established its own version of a REDD programme by creating monetary incentives for indigenous communities that agree to protect their forests instead of cutting them down.

Unlike Brazil, where squatters take advantage of undesignated territories, Peru has designated its land in the Amazon as parks and conservation areas as well as concessions for timber, Brazil nuts and other resources. Along the roads outside Puerto, however, are mostly fallowed fields in place of former rainforest, illustrating how poverty and poor soils combine to create endless pressure to clear land. Although the new federal actions are encouraging, governance remains weak and the fundamental frontier economics have not changed, says George Powell, a wildlife biologist with the WWF who is based in Peru and has become one of Asner's partners on the project.

"The forces against deforestation are getting stronger, but the forces driving deforestation are getting stronger too," Powell says one evening after the team returns from the airport to a small hotel that serves as base camp for Asner's team and for local bosses who are directing work on the InterOceanic Highway. Even as the Peruvian government paves the way for bigger trucks to haul more resources out of the jungle, he says, Asner is blazing a trail that could make carbon payments a reality and help tilt the balance in favour of standing forests. "Most people are still talking about what remote sensing can and can't do," says Powell. "Greg is already down the road putting it in the hands of users. He's three steps ahead."

Seen from the vantage of a satellite, the deforestation around Puerto extends like fish bones, following roads in long, crossing lines. These are the obvious clear cuts, where forest has been chopped down for farming. Asner's CLASLite analysis also picks up countless blips of small-scale logging far out into the forest.

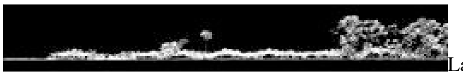
“There has to be trust in the forest-monitoring data.”
Dan Nepstad

The best Landsat images for analysing vegetation have a 30-metre resolution, which is roughly the size of a large tree crown. This misses small roads and hardwood logging operations that substantially reduce biomass levels deep within the forest and precede widespread deforestation. In 2005, Asner published a paper on the Brazilian Amazon in Science illustrating how probabilistic algorithms could be used to sniff out the hidden spectral signals of selective — and often illegal — logging (G. P. Asner Science **310,** 480–482; 2005).

That study also roughly doubled previous estimates of the amount of forest affected by human activities, while increasing the estimated greenhouse-gas emissions from the Amazon by up to 25% compared with deforestation alone. It also made a name for Asner and helped him to attract financial backing from the MacArthur Foundation, the Gordon and Betty Moore Foundation and other organizations. In total, they have given him more than $11 million to support his biomass and deforestation work, as well as other biodiversity research.

Some of that funding has gone into producing and testing a new version of CLASLite, which is designed to make it easy to conduct a biomass assessment and to set up a monitoring programme. Import a publicly available satellite image and CLASLite will correct for atmospheric conditions at the time the image was taken, then analyse the spectrum of each pixel. Vegetation that photosynthesizes has a different spectral signal from dead trees, rocks or soil. A 'Monte Carlo' analysis then produces a range of possible combinations that converge on the most likely explanation for the data. For instance, bare soil is rarely exposed to the sky in a fast-growing rainforest; if CLASLite picks up even a tiny red signal associated with the region's iron-rich soils, and that red colour extends in a line through multiple pixels, the most likely explanation would be a road.

In addition to analysing the satellite data, the software automatically pulls in existing vegetation maps and suggests locations for both aerial measurements and ground plots. In other words, the program helps to plan an integrated biomass analysis similar to the one that Asner is conducting around Puerto. "We were trying to figure out what users want, and then we finally realized they want everything, and they want to be able to hit a button," Asner says. "There's 10 years wrapped up in this little widget. That's super-secret sauce."


Laser-based measurements assess forest biomass.G. ASNER

As of this week, Asner has trained more than 240 people in six countries on the software, including several Peruvian government officials. For Peru, the project represents an opportunity to build up its scientific capacity and perhaps even leapfrog Brazil, which currently has the world's most advanced forest-monitoring programme. Deforestation is responsible for a large — and unknown — fraction of emissions in Peru, and the country is banking on REDD as a new development aid to buttress conservation efforts while reducing carbon emissions.

"It's a new issue for us, but there is a real political will to protect the forests," says Vereau. She sees the current partnership with Asner as a pilot project that could go national "if it has strong results".

Asner acknowledges the tremendous challenges ahead. He must convince not only the Peruvian government that the system works but also the broader scientific community and ultimately, perhaps, policy-makers who are debating how to restructure the global economy around carbon. But if he has any lingering doubts, they are smothered by his boundless enthusiasm. Flying over the Amazon, Asner can't help but marvel at the sights below. "Wow, there's another super-giant! That's a 300-year-old tree," he says. "These are just amazing organisms!"

Asner's work could soon have a much broader impact thanks to an agreement he recently reached with Google.org on a forest-monitoring application that would be freely available on the web. That partnership, which could be announced as early as next month, could further reduce start-up costs for tropical countries by providing them with processing power and easy access to freely available satellite data from agencies such as NASA and the Brazilian Space Agency. Asner isn't allowed to talk about it, and Google officials won't go into detail except to say that they are building a rainforest-monitoring platform and that Asner's CLASLite software will be part of the package.

Dan Nepstad, a tropical ecologist at the Woods Hole Research Center in Falmouth, Massachusetts, predicts that the remote-sensing community is on the verge of a major transformation that will open the doors to high-quality forest monitoring on a global scale. He cites progress on many fronts but says that Asner has shown a particular knack for making his science relevant and useful to policy-makers, particularly those in tropical countries. "There has to be trust in the forest-monitoring data, and these nations have to see them as their own," he says. "There's this face-to-face collaboration that is really critical."

Having spent most of his time over the past two years working to deploy his vision of REDD, Asner is now planning to shift into other projects. He is already working on an instrument for his biodiversity and biomass research that combines a more powerful LIDAR with sensors that capture reflected light in 440 frequencies. He is also taking another look at the issue of selective logging.

Asner recently completed his first, as yet unpublished, analysis of logging across the tropics and found that small-scale logging operations have a footprint that is 20 times larger than the more obvious wholesale deforestation. Right now everybody is focused on deforestation, but degradation raises a new set of scientific questions, including how much carbon is being lost and how quickly the forests will recover. Asner calls this a "future frontier science activity", which means he'll tackle the issue next year.

First, he has to finish his work in Peru. Walking along the logging road back from the Tambopata River, Asner comes across a series of trees that have recently been cut down and cast aside. They were old, hollow and unusable, but the loggers only discovered that fact after felling the trees. They could have checked the wood without hurting the trees, says Asner, by inserting a chainsaw directly into their trunks and then pulling it back out. Now the wood is simply rotting away, its carbon needlessly committed to the atmosphere.

"There are millions of trees just like this," Asner says, kicking one of the stumps. "Can you hear them falling? I can. I can hear them in my sleep."

Editorial

Nature **461**, 1027-1028 (22 October 2009) | doi:10.1038/4611027a; Published online 21 October 2009

Climate of compromise

Abstract

The chances of a strong treaty emerging from the United Nations climate talks in Copenhagen seem small, but recent progress offers hope.

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With about six weeks left before nations gather in Copenhagen to finish negotiating a climate treaty, hopes are rapidly dwindlinug that countries will be ready to sign a strong, ratifiable agreement. The pessimism has spread so widely that it could be considered a global pandemic. News stories are already talking about the 'failure' of Copenhagen and squandered opportunities.

But viewed from the perspective of just a few years ago, the Copenhagen summit could already be considered a partial success. In a short span, many nations have pledged to cut their emissions of greenhouse gases by considerable amounts, well beyond any commitments they had made before, such as through the 1997 Kyoto Protocol. Norway, for example, offered this month to reduce its own emissions by 40% below 1990 levels by 2020. Indonesia said it would curb its emissions over that same time by 26% below the levels expected under a business-as-usual scenario, with even stronger cuts possible under an international agreement. The European Union has committed to a 20% reduction below 1990 levels and would increase that to 30% with a global pact. And, for the first time, the US Congress is moving towards establishing laws that mandate emissions cuts.

These words are not to be confused with achievements, but they at least show that countries have started to analyse their own emissions seriously and to develop domestic agendas that would set them on course to meet their commitments. Such unilateral decisions are an essential starting point for an international agreement, and they suggest that countries are now ready to back up their rhetoric in a way that was not true 12 years ago, when they signed the Kyoto Protocol. This is real progress, and it would not have happened without the pressure to produce a treaty.

Nevertheless, such vows fall short of what is needed to protect against the dangers of global warming. Nations need to reduce global emissions far more in the longer term, and the endgame gets much tougher if leaders delay making those reductions.

In a package of articles this week (see below), *Nature* looks at some of the issues that will play crucial parts in the negotiations in Copenhagen. Several articles focus on factors concerning the developing world, which will endure some of the severest effects of climate change and which will also be responsible for much of the future growth in greenhouse-gas emissions. At the moment, major gaps remain between the world's wealthiest nations and those still in the process of providing their citizens with basics such as clean water and electricity.

The negotiating impasse can be breached only by concessions on both sides. Developed nations, particularly the United States, must agree to substantial reductions in greenhouse-gas emissions, both in the next decade and in the long term. And developing nations must commit to controlling their greenhouse-gas pollution in some fashion. China has recently taken over as the leader in carbon dioxide emissions and there can be no hope of containing global temperatures without Chinese action.

At the same time, developing nations will need monetary and technical assistance in steering their economies towards a low-carbon future. The wealthy nations have so far committed too little on this front, and the effects of the global recession have tightened budgets around the world. But as economies improve, the wealthiest nations should fashion innovative ways to assist the developing world, whether through the proceeds of carbon trading or through new technical collaborations.

Another major financial obstacle is the issue of support for adaptation. Some estimates suggest that the developing world will require in excess of US$100 billion in aid every year to cope with the effects of global warming. But the international funds created to help adaptation efforts in the world's poorest nations contain orders of magnitude less money, and even the available funds have not flowed smoothly to countries in need. The process of distributing funds should be streamlined. But there must be safeguards to ensure that adaptation money is used effectively.

With such major issues still unresolved, pessimistic observers see no chance of success in Copenhagen. But there is still time left for leaders to reach significant agreements if they make it a personal priority and recognize the urgency of the problem. Some leaders, such as British Prime Minister Gordon Brown, have indicated that they would be willing to attend the conference to seal a deal, but more should step forward and they should commit to going. This would lend stature to the negotiations and would raise the chances of achieving a substantial agreement.

It will not be possible to resolve many of the important issues in the remaining time this year. But leaders could make strong progress by building on the momentum at the national level. Many of the commitments made by nations this year are conditional — they depend on other parties taking specific actions as well. These could provide a model for approaching strong targets through a stepwise process.

In the end, successful international negotiations share some important characteristics with scientific research. Both are iterative processes, in which results from one step help to determine the path forward. They require time and perseverance. And they rarely travel in a straight line. Countries should endeavour to build on the positive actions of the past year, both before and after the Copenhagen summit.

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News Feature

Climate: When the ice melts

Deep in the Himalayas, the disappearance of glaciers is threatening the kingdom of Bhutan. Anjali Nayar trekked through the mountains to see how the country is adapting to a warming world.

Anjali Nayar

Kaka Tshering loops a piece of frayed jute rope around a 150-kilogram boulder. A handful of his fellow workers line up on either end and pull the rope taught.

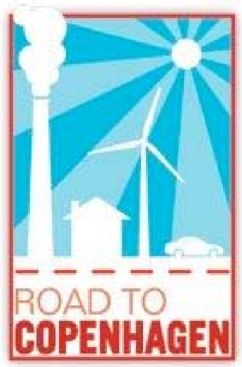
"Shochi, Shoni," the workers call in unison, as they heave. Their voices are raspy from the 4,400-metre altitude and moist, cold air. "Put your strength together."

After rocking a couple of times, the boulder rolls over and the labourers tumble backwards. Their cries are drowned out by the furious work around them as more than 300 men and women scrape away rocks with spades and shovels to reach their daily quota.

The work force is a cross-section of life in Bhutan. There are a number of young dropouts from the capital Thimphu, with greasy, shoulder-length hair and tattoos running up their forearms. Retired soldiers from the Royal Bhutan Army labour alongside former students of Buddhism. There are a handful of women in their traditional tartan-style robes, beaded necklaces and antique silver and turquoise brooches.

Together in matching hard hats and leaky rubber boots, they make up Bhutan's army against the effects of climate change. Their task is to deepen and widen the outlet channel from lakes formed by the rapidly melting Thorthormi glacier. By helping the water to drain faster, Bhutanese officials hope to prevent a catastrophic flood.

Glaciers in the Himalayas are retreating faster than in any other part of the world and they could disappear completely by 2035 (ref. 1). This puts the mountainous nation of Bhutan at a special risk. In an area smaller than Switzerland, it has 983 glaciers and 2,794 glacial lakes, some of which have burst to produce deadly glacial lake floods.



Online collection

As a poor nation without even its own helicopter, Bhutan lacks the resources to combat global warming. It is carrying out the work at Thorthormi glacier with the help of money from various international donors, including US$3.5 million from the Least Developed Countries Fund, created under the United Nations Framework Convention on Climate Change. The global cost of adaptation could total hundreds of billions of dollars a year — orders of magnitude more than what is available to poor countries at the moment. During December's UN talks in Copenhagen, developing countries will be pushing for more generous — and reliable — funding to help them mitigate the impacts of climate change. As the first nation to get adaptation money from the Least Developed Countries Fund (see 'The long wait for adaptation money'), Bhutan is something of a pioneer among developing nations in their quest to adapt to a warmer future. And the struggles at Thorthormi glacier illustrate the enormous obstacles that adaptation efforts still face.

Dangerous dam

The sounds of global warming are deafening at Thorthormi glacier. Every few minutes, a block of ice rips off the glacier and crashes into the lake in a trail of dust and ice. These are some of the tallest mountains in the world and form Bhutan's northern boundary with Tibet.

To get a look at the hazard posed by the melting glacier, Karma Toeb, the project's glaciologist and team leader, scrambles to the top of a moraine — a steep ridge of loose, angular boulders built up by the glacier as it pushes debris along its edges. This moraine is a dam between two bodies of water (see map). To the east, Toeb points out how several slushy grey-brown ponds have formed on top of the Thorthormi glacier. To the west lies a much larger lake called Rapstreng — vast and milky green — about 80 metres lower in elevation. Toeb first came to this site in 1997, during a project to shrink Rapstreng lake. Over three years, a thousand labourers widened and deepened Rapstreng's natural outlet to lower the lake by 4 metres.

At the time, nobody was worried about the Thorthormi glacier next door. "Thorthormi was almost pure ice," says Toeb. "We could cross over and walk on the glacier to do our research." The glacial lake didn't even appear in an exhaustive study of the region's dangerous lakes in 2001 by the International Center for Integrated Mountain Development (ICIMOD), based in Kathmandu, Nepal[2,3].

It is only within the past decade that researchers realized that Thorthormi could pose a threat. Thorthormi's ponds were expanding and merging to form larger bodies of water. The changes have been dramatic even in the past few months. "Just before we started our work here in July this year, that part of the lake was water," says Toeb, pointing down to a number of icebergs. "The ice blocks have been breaking off the mother glacier upstream."

But the rate at which Thorthormi glacier is melting is not the only concern, says Toeb, motioning at the boulders underfoot. The moraine separating the Thorthormi and Rapstreng lakes is at places only around 30 metres wide and is prone to landslides. Geophysical testing in 2008 showed that the moraine contains a substantial amount of ice. As that ice melts, along with the rest of the glacier, the ridge could collapse, releasing the water from Thorthormi into Rapstreng below. Then there would be a combined outburst flood, Toeb says.

Building pressure

A four-year study led by Hermann Häusler from the University of Vienna in collaboration with Bhutan's geology and mines department predicted the moraine between Thorthormi and Rapstreng could give way as early as 2010, because of the hydrostatic pressure of the growing Thorthormi glacial lake. A combined flood would unleash around 53 million cubic metres of water down the Pho river[4].

Every country within the Himalayan region has suffered a glacial outburst flood at some point[3], and Bhutan is no exception. A number of glaciers in that country are missing sections of their moraines, suggesting that lakes have burst there in the past. Half a century ago, floods originated from the Lunana region in northern Bhutan, which is home to Thorthormi and many other glaciers. The floods may have come from glacial lakes, but there were no studies of them at the time. The only scientifically documented glacial flood in Bhutan's history came from a lake at the bottom of Luggye glacier, on Thorthormi's eastern margin, 15 years ago.

Ponds first appeared on the Luggye glacier in the late 1960s, and by the early 1990s the glacier was retreating by up to 160 metres a year[2]. On 7 October 1994, the glacier's moraine broke and released an estimated 18 million cubic metres of water and debris down the Pho river, killing 21 people and razing fields and settlements downstream with a jumble of uprooted trees, boulders and mud.

Memories of that flood still haunt Dawa Gyeltshen, a herder who lives in the village of Taksho, beside the Pho river around 20 kilometres downstream of Luggye. He remembers being woken by a thunderous noise early that morning. For hours he raced around outside his house in the dark, terrified as the river rose.

It wasn't until dawn that Gyeltshen saw the extent of the damage. The forested river valley and a large portion of the fields in front of his house had been washed away and in their place were mounds of boulders and glacial silt. Today, the landscape is recovering. Pockets of shrubs and wildflowers have settled in along the river and Gyeltshen's remaining land is golden with this year's crop of buckwheat. White prayer flags line the rugged edge of the property, marking the course of the water during the flood. But even now, Gyeltshen says he still has trouble sleeping through the night, worried about another flood.

A combined flood from Thorthormi and Rapstreng lakes could cause at least ten times the damage and fatalities of the 1994 event[4]. In the past 15 years, hospitals and schools have popped up along the river, along with a partially completed $760-million, 1,200-megawatt hydropower dam project.

It was in part because of the 1994 disaster that Bhutan became a leader in adapting to climate change. Following the flood, scientists from Bhutan, Japan and Austria, among other countries, launched research programmes into the glaciers in the Lunana region. When the Least Developed Countries Fund was created in 2001, "we had a lot of good information on glacial floods", says Thinley Namgyel, the deputy chief environment officer at the National Environment Commission in Thimphu.

Gross national happiness

Bhutan's work on adaptation is backed by a strong record of environmental protection. As a follower of the Buddhist tenet of non-extremism — the Middle Path — Bhutan's monarchy has stressed that modernization and economic development are important, but not at the expense of the country's natural environment and cultural traditions. In 1972, Bhutan's fourth King, Jigme Singye Wangchuck turned away from the classic yardsticks of growth, such as gross domestic product, to focus on a more holistic approach to his people's well-being. The measurement, which he called gross national happiness, is based on several measures of environmental and social contentment.

The country has some of the most progressive — and controversial — environmental regulations in the world, including bans on plastic bags, timber exports, hunting and even tobacco sales. They've also minimized tourist traffic by charging visitors to the country around $200 a day.

The nation's proven environmental record, coupled with the immediacy of the risks of a glacial flood, made Bhutan's adaptation needs especially attractive to donors. "From the start, Bhutan was in the driving seat," says Bonizella Biagini, a senior programme manager at the Global Environmental Facility, which manages the Least Developed Countries Fund. Other developing nations have been less successful in getting adaptation money through that fund. "If everyone behaved like Bhutan, every project would be in the process of being implemented," says Biagini.

Bhutan has also received $1.3 million in adaptation support from other sources, including the Austrian Development Cooperation, the conservation group WWF Bhutan and the United Nations Development Programme.

Yet even with money and political will-power, the task is daunting. The main goal at Thorthormi glacier is to lower the lake's water level by 5 metres, which would reduce the hydrostatic pressure pushing on Thorthormi's unstable natural dam.

Under normal conditions, the lowering would be an easy task, but the remote location of the lake, the extreme altitude, the boulder-strewn terrain and the unpredictable weather have made the project logistically difficult.

“All the lakes need attention. But we have to prioritize where we do the big-scale mitigation work.”
Pradeep Mool

The project's engineer, Karma Tenzin, had hoped originally to fly a couple of excavators to the site and do the digging in a few weeks. But soon after visiting Lunana this year, he realized an industrial solution would be difficult. The nearest potential helicopter landing was an hour and a half away by foot. Even if an excavator was brought in, it could topple on the uneven terrain, says Tenzin. "Everywhere you look are boulders," he says. "Bringing in an excavator is useless."

The price was also a factor: without its own helicopter, Bhutan would have had to hire one from Nepal for several thousand dollars per trip. Because unemployment is rising in Bhutan, the project board reasoned that it would be better to pump the money into the country's economy — by paying local horsemen to transport the project's goods and by providing excavation jobs. So in July, in the middle of the monsoon season, hundreds of workers set off on the 9-day journey to Lunana from the capital. At the site, using shovels and spades, they load cobbles into strips of burlap and carry them to the sides of the channels. Boulders are broken crudely with blunt hammers and hauled off-site with weathered rope. At the end of September, a few jackhammers and chisels arrive to help split boulders. A shipment of rope also arrives, although Tenzin admits that it is unlikely to last long. "At least for the next two weeks we will be able to pull rocks," he says. "After that, the rope is likely to be all broken again."

The working season for the project is less than four months a year, because snow blocks the path to the site for all but July to October. But heavy rainfall this year washed away several key bridges, delaying work for an additional month. "We almost cancelled the project for this year," says Dowchu Dukpa, the project's manager. "We thought: by the time we get there, we will have to go back."

But the project went ahead. When the last workers put down their tools for the year on 15 October, they had lowered the lake by around 90 centimetres. This was considerably less progress than the original goal of 1.67 metres for this first year, but the group thinks it can make up the difference during the next two years of the project. "I am sure the goal will be achieved," says Tenzin.

Practical challenges

Even if the final goal of 5 metres is achieved by 2011, glacial experts cannot say how much that will reduce the risk of a moraine burst. Part of the problem is the lack of basic information about the Thorthormi glacier and its lake.

The glacier is covered in boulders and silt, which makes it difficult to measure how quickly the ice is retreating, says Koji Fujita, a glaciologist from the University of Nagoya in Japan.

The lake's drifting icebergs also make a comprehensive bathymetric survey extremely dangerous, says Fujita. Bhutanese officials only took a few depth measurements in 2008 with a simple string and weight, because strong winds made it difficult to handle the boat. "We don't know how much water will come out of the lake or how fast it will flow in an outburst," says Fujita.

What's more, developing countries such as Bhutan don't have the technical and financial resources to study the changes that are happening in their countries. High-resolution satellite imagery can be expensive and the country can afford it only infrequently. Difficult and remote terrain also hampers their monitoring work. Every scientist and bit of instrumentation has to make the journey to Lunana on foot. To top it off, they are contending with a landscape that is rapidly changing because of global warming.

Project leaders reason that their strategy at Thorthormi must reduce the hazard there to some degree. "If the lake is lowered by some metres, that much pressure is released from the moraine wall," says Toeb. "So the chance of the moraine wall failure is less."

But Toeb admits that the work will not eliminate the possibility of a flood. "A piece of ice could detach from the mother glacier, fall into the lake and generate a surge wave," says Toeb. "Or if there is a big seismic event in this area, the whole moraine wall surrounding the glacial lake may collapse."

Because artificially lowering Thorthormi isn't enough to prevent a flood, the government intends to install an automatic flood early warning system in the Pho river valley, which will also be paid for with money from the development fund.

The Bhutanese Department of Energy currently runs a manual warning system in the Lunana region. A couple of attendants equipped with a VHF radio and satellite phone are supposed to monitor the lakes and river three times a week. But the system isn't working. "We never see them at the site," says Toeb, who has reported the problem to the department.

The new automatic system will record the water levels using sensors. In the case of an outburst, the system would send out a signal to towers downstream to warn communities of an impending flood, potentially providing hours of advance notice.

Because Bhutan does not have the capacity or expertise to do the work on its own, its Department of Energy has put the project out to tender, in hopes of an international bid within its budget. Construction is expected to start next year, says Karma Chhophel, the head of the department's hydrological- and meteorological-services division.

The entire Thorthormi mitigation project will last at least four years and cost $7.4 million. But Thorthormi is only one of thousands of glacial lakes in Bhutan. ICIMOD has identified 25 potentially dangerous lakes in Bhutan, but the list was based on crude satellite data[2].

The centre will release an updated inventory of dangerous lakes in Bhutan next year based on satellite imagery with "better spectral, spatial and temporal resolution", says Pradeep Mool, a remote sensing specialist with ICIMOD, who was involved in the study. The inventory will also rank lakes based on socioeconomic information, including the potential loss of life and damage to infrastructure. "All the lakes need attention," he says.

"But we have to prioritize where we do the big-scale mitigation work, the early-warning system, and the hazard zonation maps."

Spy data

But qualitative analysis of satellite images isn't enough to determine which lakes are dangerous, according to Fujita. He is trying to develop quantifiable criteria, such as the angle between the level of the water in the glacial lake and the slope of the moraine, that dictate a moraine's stability and the likelihood of a glacial outburst. His team is testing that hypothesis by comparing new satellite images with data from old American spy satellites to create digital elevation models of lakes that burst in the past. The researchers will also develop their own list of the region's dangerous lakes next year, but the results are likely to be substantially different from ICIMODs, says Fujita. "Some of its 25 dangerous lakes are not a hazard, but we found more that ICIMOD did not point out," he says.

Regardless of which lakes are a risk now, the number will rise in the future, as glaciers continue to melt. "Thorthormi is a very good lesson," says Toeb. "Nobody knows what will happen, taking into account all the changes in climate; the same situation may happen to any of the glaciers in Bhutan."

Although glacial lake bursts cause considerable damage in the Himalayas, an even bigger catastrophe would come from the disappearance of those very same glaciers, and the water they produce, which is predicted within the next few decades. That loss could significantly harm the 69% of the Bhutanese population that relies on farming, mostly subsistence. A decrease in water flow could also seriously affect the country's plan to boost its hydropower production by 10 gigawatts by 2020. "We don't know the medium- or long-term costs of climate change in Bhutan," says Namgyel. "A few decades down the line, the glaciers will retreat and we are not sure what impact it will have on the economy."

The impacts will reach far beyond Bhutan's borders. The glacier-fed rivers that flow south from the Himalayas are the arteries of south Asia. It is estimated that the retreat of glaciers will affect the water supply of roughly 750 million people across South Asia and China, says Rajendra Pachauri, the chairman of the Intergovernmental Panel on Climate Change.

Across Asia, there are countless cases like Thorthormi, where the needs are great and the resources scarce. Regarding the effects of climate change and their costs, "every single estimate that people have come up with has been exceeded by reality", says Pachauri. "The impacts of climate change are clearly turning out to be much worse than what we had anticipated earlier."

Standing on Thorthormi's natural dam, the scale of the problems ahead strain the imagination. From here, the sounds of the labourers struggling 100 metres below fade to whispers on the wind. At this distance, it is impossible to see their frost-bitten cheeks, or the cuts and bruises earned during their months of labour. In a line of 30 people, they look like a caterpillar pulling pebbles across a path. They are dwarfed by the size of the lake, the glaciers above, and the mountain of work confronting Bhutan and the rest of the world, as it tries to keep pace with the changing climate.

See Editorial, page 1027, and online at http://www.nature.com/roadtocopenhagen a video at http://go.nature.com/VGGayN.

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- ## References

1. Cruz, R. V. *et al.* Asia. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (eds Parry, M. L., Canziani, O. F., Palutikof, J. P., van der Linden, P. J. & Hanson, C. E.) 469-506 (Cambridge Univ. Press, 2007).
2. Bajracharya, S. R., Mool, P. K. & Shrestha, B. Impact of Climate Change on Himalayan Glacier and Glacial Lakes: Case Studies on GLOF and Associated Hazards in Nepal and Bhutan (ICIMOD, 2007).
3. Mool, P. K. *et al.* Inventory of Glaciers, Glacial Lakes, and Glacial Lake Outburst Floods: Monitoring and Early Warning Systems in the Hindu Kush-Himalayan Region, Bhutan (ICIMOD, 2001).
4. Brauner, M., Leber, D. & Hausler, H. Glacier Lake Outburst Flood (GLOF) Mitigation Project, Lunana, Bhutan, Technical Mitigation Measures Thorthormi Outlet. (Department of Geological Sciences, University of Vienna, 2003).