Chapter 11

Highland zones: the rapid change of Andean environments

View of Chimborazo from the slopes of the Altar volcano in Ecuador.

Tropical highland areas are among the regions where the impact of climate change is most marked. The retreat of tropical glaciers is spectacular, especially in the Andes, the site of 99% of tropical glaciers. The area of these glaciers has decreased by 30 to 50% in about 30 years. Melting ice has had many consequences for the hydrology of drainage basins and hence on water supply and the dynamics of highland environments. Future changes promise to be just as important as climate projections forecast a very substantial warming of high mountain tropical ecosystems—this could reach +3°C by the end of the century.

IRD has carried out research on Andean glaciers and mountain environments for about 20 years. Glaciologists, climatologists, hydrologists, ecologists, agronomists and modellers are thus developing a multi-disciplinary approach aimed at better understanding of the mechanisms of the melting of ice, its role in the hydrology of drainage basins, the sensitivity of biodiversity to these changes and other features.

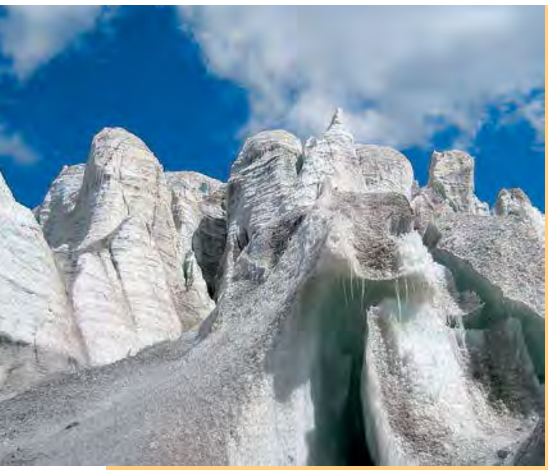
The Andes are also an excellent area for observing fine trends such as the evolution of biodiversity in relation to climate change as mountain ecosystems are still comparatively well preserved in comparison with other environments (coastal zones for example) where numerous anthropic pressures make it more difficult to describe climatic factors.

Retreat of glaciers and water resources

Tropical glaciers are very sensitive to global warming. Since the 1970s, precipitation has changed little but the air temperature in the tropical Andes has increased by 0.7 °C. Although the temperature is not directly responsible for melting at this altitude, it affects the nature of precipitations—solid or liquid—and therefore the snow cover. The latter helps to reflect the greater part of the solar energy received. Without snow, the melting of glaciers increases considerably. Glaciers lacking snow cover have tended to become more frequent in recent decades.

Box 29

The annual variation of the mass of a glacier is a good climate indicator



The Zongo glacier at the summit of the Huayna Potosi (Bolivia) has retreated considerably in recent decades.

Very few climatic data are measured directly by meteorological stations in high mountain regions. IRD is therefore working on strengthening climate observation services in the various Andean countries (see Part 1, p. 43).

Among important observations, the annual variation of the mass of a glacier is a good climate indicator as it represents a balance of inflow and outflow over the year. Snowfalls form the main incoming mass and losses result above all from the melting of ice or surface snow. Measurement of the annual mass balance is thus a direct record of the meteorological conditions that govern the processes of accumulation and ablation of snow and ice at the surface.

LTHE researchers successfully completed for the first time measurement operations on turbulent flow at the Zongo glacier in Bolivia. This research has led to better description of the special features of tropical glaciers. In the tropics, ablation takes place throughout the year whereas accumulation is during the rainy season. The climate change observed for several decades is tending to raise the rain/snow limit, causing more ablation and less accumulation. The monitoring of mass balances gives better understanding of the relation between climate and glaciers. They also provide information for comparing melting and accumulation processes in varied regions (polar, temperate and tropical latitudes), showing marked differences in relation to the climatic context.

The research carried out by IRD and its partners has shown an increase in the melting of Andean glaciers in the last 40 years. The areas of the glaciers in Colombia, Ecuador, Peru and Bolivia have decreased by 30 to 50% since the end of the 1970s. Small glaciers (less than 1 square kilometre) at altitudes of less than 5,400 m are those most affected insofar as their accumulation zone (where snow gathers and then turns to ice) is small. If the increases in temperature forecast by climate model by the end of the century are confirmed, most of the glaciers—large and small—in this part of the Andes may disappear. This happened to the Chacaltaya glacier above the city of La Paz in Bolivia in 2010.

Glaciers, water reserves for dry periods

The role of glaciers in the hydrological functioning of mountain drainage basins varies considerably from one region of the world to another. It is often minimal in temperate zones like the Alps where winter snow cover and precipitation are substantial. However, in tropical regions where the seasonality of precipitation is marked by a dry season lasting for several months when no snow layer can form, glaciers play a significant role in the flow of the rivers below.

The Andean glaciers are thus important regulators of seasonal water cycles. They serve as reservoirs of frozen water and flow during dry periods, feeding watercourses downstream. Glaciers can contribute as much as 25 to 30% of the hydrological regime in certain drainage basins with some 20% glacierisation. In arid regions as in Bolivia and Peru, glaciers can make a very significant contribution to irrigation, hydroelectricity and the water supply for local populations. Thus 15% of the water used in La Paz comes from glaciers and the figure rises to 30% during the dry season.

Better understanding of the impact of glacier retreat on the availability of water

Climate change scenarios for the coming decades predict an increased rise in temperatures in high mountain tropical ecosystems. If the trend continues, the first features will be faster melting and increased runoff in high altitude sub-basins, increasing the quantity of water available downstream. But subsequently, when the volume of the glacial reservoir has decreased, there will be less meltwater than there is today. Droughts could become more serious than they are now and less water will be available for various uses such as agriculture, potable water consumption or hydroelectricity.

Researchers are evaluating the state of water resources according to the degree of deglacierisation to better understand the impact of the retreat of glaciers on hydrology. Work has been focused in particular on the river Santo in Peru, an emblematic river as it is supplied to as much as 50% by glaciers, depending on the season.

The Zongo glacier on Huayna Potosi mountain (Bolivia).
The increased rate of ice melt increases the quantity of water available downstream.
But the trend will be reversed when glacial reserves have been depleted.

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Box 30

Calculating the contribution of glaciers to water resources downstream

Glaciers store water at the scale of several decades and thus form reservoirs that directly affect flows downstream.
Understanding and quantifying meltwater supply in the context of climate change and glacial retreat are therefore of prime importance for monitoring the evolution of present and future water resources.
However, studying the role of glaciers in the hydrology of a drainage basin is complex.
Clear distinction must be made between the proportion of water stored annually as snow and then flowing as liquid water when it melts and the proportion truly originating from glacier retreat and the variation of this stock.

The study of these phenomena requires careful monthly measurement of precipitations and the rate of ablation/accumulation of snow on the glacier.
The latter glaciological measurements consist of recording levels on indicators (posts driven into the ice) and digging holes in the accumulation zone to calculate the mass balance.
The measurements of mass balance combined with measurements of precipitation show the volume of water resulting from snow and ice melt at the glacier and flowing downstream.

Combining measurement methods for better evaluation

Three other methods are also used to quantify the contribution of glaciers: direct flow measurements in rivers, measurements using hydrochemical tracers and hydrological balances performed using modelling.
Hydrochemical measurements are based on the analysis of stable isotopes in water and major ions as the different sources of flow have specific chemical signatures and it is therefore possible to quantify glacial flows.
Hydrological modelling consist of simulating the different types of flow by using geomorphological data that are characteristic of the drainage basin and meteorological forcing data (temperature, precipitation, radiation, wind, etc.).

The ideal approach consists of combining several of these methods to evaluate the agreement of the figures obtained. Three drainage basins are being examined thoroughly within the framework of the international mixed laboratory Great Ice: the Zongo basin in Bolivia, the Antisana mountain glacier in Ecuador and the river Santo that is fed partly by the glaciers of the Cordillera Blanca in Peru. Glacier flows vary in time and space. For example, more glacier water flows into the river Santo during the dry season (more than 50% of flows) than during the rainy season (about 30%).

Glacial stream opposite Cotopaxi in Ecuador.
Direct measurement of the flows makes it possible to calculate variations in flows from glaciers.

High mountain biodiversity faced with climate change

High mountain regions in the tropics are isolated islets where the migration of new species is limited and speciation enhanced. Low temperatures, low atmospheric pressure, intense solar radiation, irregular rainfall, dry winds, frost, etc. are all extreme conditions that encourage singular adaptations in the varieties present. Glacier streams are also a difficult habitat because of their low mineral content and daily high water generating strong disturbances. The tropical Andes house a high degree of endemism with species that are unique in the world but because of this there is an inexorable risk of extinction if the ice continues to retreat.

The first cases of extinction

Andean aquatic species are among the first to suffer population extinction caused by climate change. As mountain streams have been changed considerably by the acceleration of melting for the last 40 years, scientists focused on the fundamental role of meltwater for aquatic life. They observed that glacier retreat has endangered a proportion of the invertebrates that live in rivers (Box 31). The ecological role of most of the endangered species is still not known and the consequences for higher animals—fish, amphibians, birds and mammals—remain difficult to forecast.

Migration of species

A 3°C rise in average temperature in the tropical Andes could cause plant species to migrate upwards by nearly 600 m. Such a change in mountain ecosystems would result in a significant reduction of the habitat available for numerous species. Indeed, mountain species have limited space and are 'stuck' between high and low. At the high end, factors associated with altitude such as strong UV radiation or lack of oxygen limit the survival of certain species. At the lower end, competition with other, flexible species—that is to say that can prosper in a large variety of environmental conditions—that colonise more favourable thermal niches encourages the mountain species to continue to migrate upwards. They thus suffer stronger reduction of their distribution area than those observed in other places in the world. Isolated in limited areas, the populations of mountain species are particularly exposed to extinction processes.

Sentinel species

Climatic factors other than glacial retreat also affect biodiversity. The rise in temperature and the increase in UV radiation are thought to be partially responsible for the

Box 31

The retreat of glaciers is a threat to aquatic biodiversity

The melting of Ecuadorean glaciers has caused the extinction of several aquatic species. If the glaciers were to melt entirely, 10 of 40% of the regional richness in species would risk disappearing.

IRD ecologists and their European and Ecuadorean partners have studied the biodiversity of streams fed by meltwater in the Andean *páramos*. These very special herbaceous ecosystems are characteristic of Andean peaks at over 3,500 m between the treeline and permanent snow. A fair number of the species—mainly insects—that inhabit the watercourses in these extreme environments are endemic.

The scientists collected samples at some 50 different places in the *páramos*. They counted the populations of macro-invertebrates—mainly larvae of species that belong to the orders Ephemera, Trichoptera or Diptera.

In over a year of regular sampling, the scientists identified more than 150 invertebrate species in the *páramo* of the volcano Antisana alone.

From 10 to 40% extinction

Samplings performed at different distances from the glaciers showed that local species richness in the Andes increases towards downstream. It also appears that the populations of the various streams at the same altitude are markedly heterogeneous. The communities observed about a hundred metres apart in two streams of similar appearance can be very different depending on the glacier drained. Andean glaciers have varied dynamics and melt at different rates according to their size and exposure to the sun for example.

This sampling, combined with monitoring data concerning the aquatic communities, showed that several species start to disappear as soon as the glacial cover decreases to less than half of the drainage basin area. And if the glaciers melted entirely, 11 to 38% of regional biodiversity would risk disappearing, depending on the zone in question.

Analysis of glacial streams in the Paramo region, Ecuador.

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Box 32

Modelling the impact of climate change in a key ecosystem in the tropical high Andes

The international project BIO-THAW, with European (including IRD) and Andean partners is aimed at understanding and modelling the impact of climate change on a key high Andean ecosystem, the *bofedales*. Biodiversity is exceptional in these high altitude (4,000 to 5,000 m) wetland ecosystems.

With organic soils several metres deep, they have exceptional water retention capacity and supply millions of people downstream, even during the dry period. Furthermore, plant productivity is comparatively high all the year round and millions of head of livestock are produced, especially llamas and alpacas.

The multidisciplinary approach in the BIO-THAW project uses recent glacial retreat as an indicator of climate change, with the underlying hypothesis that the decrease in water supply to the *bofedales* will damage their biodiversity and functioning. All the data collected (in glaciology, remote sensing, ecology, agronomy and sociology) will be compiled in a multi-agent model.

Climate change scenarios predict increased warming in high mountain tropical ecosystems in the coming decades. Characterisation of the sensitivity of these ecosystems to climate change and putting forward solutions for maintaining their optimal functioning form a scientific and societal priority.

Sampling water in a highland wetland (4,800 m). Cordillera Real, Bolivia.

© IRD/O. Dangles

Harlequin frog
(*Atelopus* nov. sp. ?)
Sangay National Park
(2,200 m), Ecuador.
A broad diversity of amphibians including numerous species that are endemic to subtropical forests is found on the eastern slopes of the Andes.

extinction of frogs of the genus *Atelopus*, amphibians that are very sensitive to changes in the environment. This previously abundant group of Andean frogs has now become much rarer and has even disappeared in some regions since the end of the 1980s. Although there seem to be many causes, scientists have demonstrated the contribution of exceptional climatic conditions and high UV levels. These frogs are a sentinel species and also early indicators of the decline of other species.

Climate change and microclimates

The Andean valleys have a mosaic of very heterogeneous landscapes set at intervals on mountains slopes in different microclimates. The study of these microclimates is particularly important today for understanding the response of living species to climate change. The behaviour and survival of organisms depend on the dominant environmental conditions at their scale. These local climatic conditions often differ from the regional climatic situation.

Box 33

Temperature differences that can double between local reality and regional extrapolations

The differences between local temperatures and information provided by the WorldClim database were measured in a study in the Ecuadorean Andes. The results show that microclimate conditions generate overestimates and underestimates of some 80% for the minimum and maximum temperatures predicted by the global models.

In order to evaluate the capacity of meteorological systems to provide information about biological processes, the EGCE unit and its South American partners addressed the difference between the temperature data provided by the WorldClim database (extrapolation for a 1 sq. km mesh) and actual measurements in agricultural landscapes in the Ecuadorean Andes.

The researchers first showed the heterogeneity of temperatures in the fields according to the relief and also according to the precise site of measurement (soil, crops or air). They then compared these data with the WorldClim database. The results show that microclimate conditions, and especially those caused by the structure of the vegetation, generate overestimates and underestimates of some 80% in the minimum and maximum temperatures predicted by the global models. The differences were most marked when temperature was measured at the level of crop foliage or in the soil since these habitats play the role of buffer reducing thermal contrasts.

The difference in the increase of crop pests using WorldClim and local measurements was then examined. The results show the limits of models that are based on too large a mesh for the prediction of the dynamics of insect populations in regions where there are very varied microclimates.

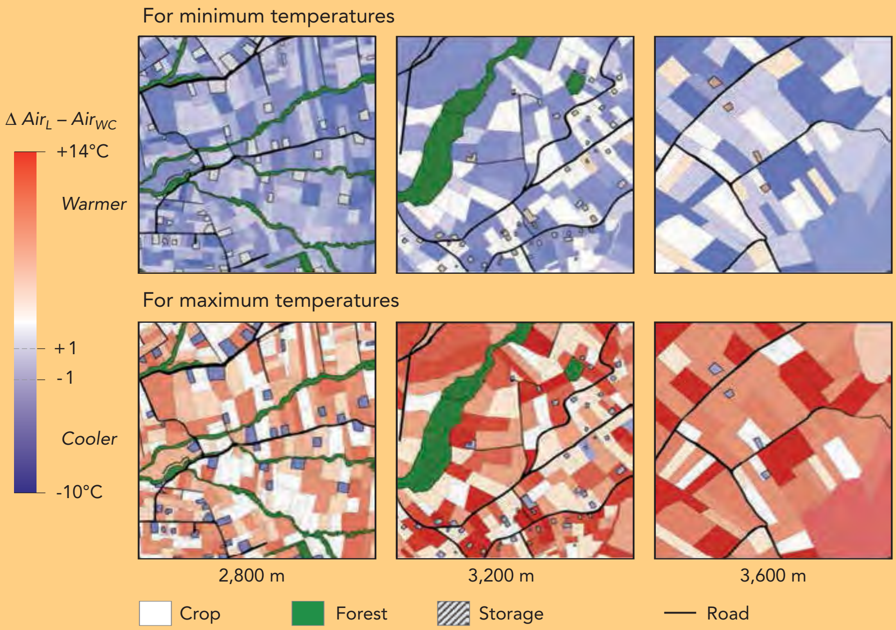

Figure 24.
Microclimates in farming areas in the Ecuadorean Andes.
Differences in minimum and maximum temperatures between local measurements and data supplied by WorldClim. The zones in which local temperatures are lower than those provided by WorldClim are in blue; zones in which local temperatures are higher than those provided by WorldClim are in red, and zones in which the zones are equivalent are in white.
Source: after FAYE *et al.*, 2014.

A question of scale

It is therefore urgent to know how regional warming affects microclimatic conditions in order to find out its effects on species. Scientists are addressing this question of scale—between the large mesh of climate models and the fine mesh of microclimates—by combining global and local approaches. By improving species distribution model at different scales, climate simulations will then allow better forecasting of biological changes. This information is also important for improving agricultural forecasting as crop growth is directly related to local temperatures.

The impacts of warming on crops in the altiplano

Farmers in the high plateaux in the Andes have always had to handle climate uncertainty. Night frosts are a source of major stress for crops at an altitude of nearly 4,000 m. It even freezes in the summer, especially in the plain where cold air accumulates. To handle this climate risk, over the centuries farmers have developed original agricultural techniques and dozens of local varieties with great genetic diversity.

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Potatoes grown on terraces in the Peruvian Andes. This crop is found at 2,000 m to 4,500 m with a specific potato variety for each stage of altitude.

Climate risks have changed in the Andes in recent decades because of climate change and also following change in land use. This is illustrated by the increase in quinoa growing in the southern part of the Bolivian altiplano. The commercial success of this grain means that production increases from one year to the next: the cultivated area in the region tripled from 1972 to 2005. Farmers have cultivated land in the plains where mechanisation is easy but it is *a priori* more at risk from frost than the slopes. So far, climate warming has tended to favour the spread of cropping as it has reduced the risk of frost in the plain and extended the climate zones favourable for quinoa, which have gained several hundred metres in altitude.

However, the rapidity and complexity of the changes observed—that depend on both climate and land use—might affect soil and climate conditions more drastically and have negative effects on crops. Projections combining agricultural production and climate scenarios show that after a favourable but transitory effect of a decrease in frost risk, the probable increase in drought periods in the coming decades will reduce yields (Box 34).

A farmer attending a pest control training session at Chaopcca, Peru.

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Ecological interactions and crop pests

The effects of climate change on ecological interactions will also influence agricultural yields. All species interact with other species, whether predator and prey, parasite and host or pollinator and the plants visited. The effects of climate change on the most sensitive species will have knock-on effects via these interactions and particularly along food chains. Some biologists consider that these impacts on interactions between species could weigh more on biodiversity than the direct impacts of climate.

In the Andes, scientists have examined in particular how changes in temperature affect the inter-species relations of crop pests and the effects on attacks of plants. The studies show that there is no linear effect between temperature and attacks by insects and other pests because of the complexity of their interactions

Box 34

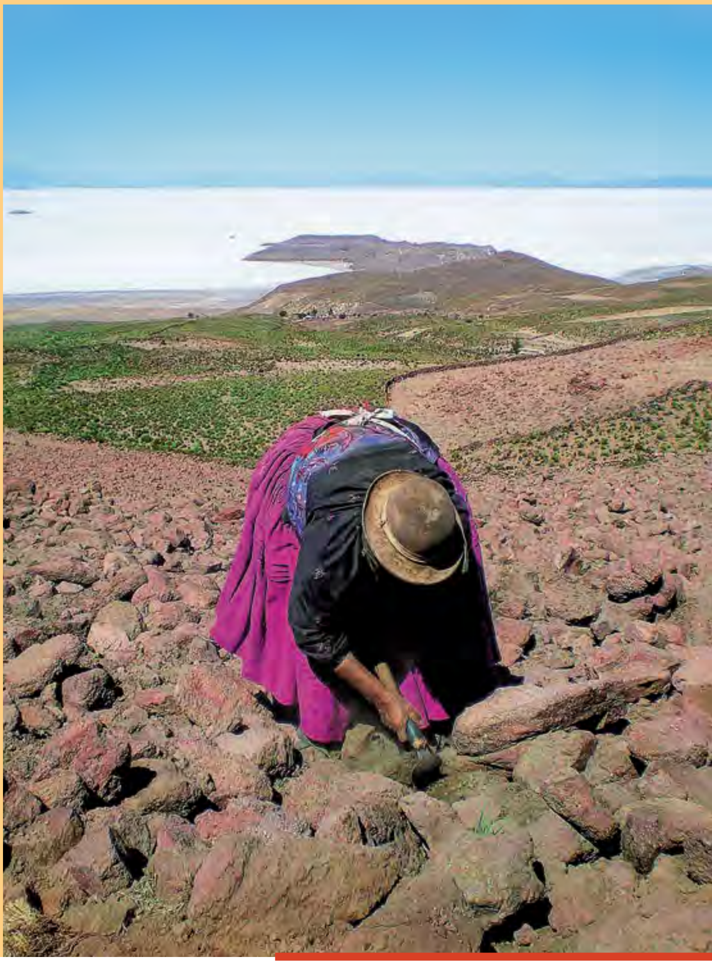
Assessment of quinoa production according to climate scenarios

Quinoa production on the arid altiplano in southern Bolivia depends to a considerable degree on soil moisture and frost risk.
IRD scientists and their Bolivian partners modelled the evolution of the crop in 2050 and 2100 using commonly accepted climate scenarios.

To gauge the local impact of climate change, the researchers made a distinction between two types of landscape while still working at the scale of an entire region—the area around the Salar de Uyuni (a salt flat).
This semi-desert zone with frost more than 250 days a year used to be shared between crop and livestock farming.
It is now the world's leading quinoa export region.

Simulations show that after the present production peak resulting from a decrease in risk of frost and the use of grazing land for crops, production could decrease markedly as a result of the increase in periods of drought, the saturation of agricultural land and loss of soil productivity.

Modelling uses climate and land use, two major components of global change and too often dissociated in research work. For local stakeholders, this forecasting exercise provides material for the debate about the sustainability of their development choices in a changing climatic and socioeconomic context.



Quinoa on the flank of Tunupa volcano in Bolivia.

and different thermal optimums from one species to another. Thus, according to the temperature conditions to which they are subjected, pests may either compete with each other or in contrast maintain positive interactions (facilitation for example). The researchers are therefore refining the forecasting models by incorporating the complexity of biological interactions.

Box 35

Kenya: another example of a highland region where warming will increase pest damage to crops

Maize is the main food resource in East Africa and is grown on nearly 80% of the cultivated area in the region, especially on the slopes of Mount Kilimanjaro and the Taita Hills. The small yields of some 1 to 3 tonnes per hectare are attributed to poor climate conditions and insects. Climate change will probably make these constraints more marked.

The studies carried out since 2010 by unit 72* in these mountainous parts of Kenya provide better understanding of the effect of temperature and altitude on the distribution of the two main pests found on maize (*Chilo partellus*, an exotic member of the Crambidae family and the indigenous moth *Busseola fusca*). The researchers also examined the distribution of natural enemies of the pests (larval parasitoids) to take into account the interactions between species. Their work confirms that temperature is a key factor in these interactions and partly explains the predominance of C. *partellus* at low altitudes and that of B. *fusca* at high altitudes.

The crambid migrates more quickly than its parasite

Using phenological models of the presence and activity of the pests and their parasitoids according to the climate, the researchers generated risk maps based on meteorological data from local weather stations and IPCC climate scenarios.

Their forecasts suggest that increased pest activity linked with warming should result in a significant increase in maize crop losses in all the agro-ecological zones studied; the figure is between 5 and 20% depending on the altitude and the pest species. Altitude aggravates the impact with the extension of the distribution area of the crambid to above 1,200 m

* Biodiversity and evolution of plant/insect pest/antagonist complexes.

and the slower shifting of its natural enemy. This should result in less effective biological control of the pest at altitudes of over 1,200 m.

An increase of silica in maize with temperature

As maize uses an accumulation of silica in its tissues to protect itself against certain pests, including the moth, the researchers also wanted to understand how the increase in temperature could change silica contents in the plants. The results show that concentrations of silica in the soil and maize decrease with altitude and that uptake of silica by maize increases with temperature. This confirms the thermal optimums of the two species and explains the predominance of the moth at high altitudes.
In the future, warming should increase plant uptake of silica and therefore enhance the movement of the crambid to higher altitudes.

Maize infested by the African maize stalk borer (*Busseola fusca*) in Kenya.

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