improved insurance programmes. Results of existing benefit–cost analyses support such flexible strategies for NYC[6].

Rosenzweig and Solecki also address important barriers to the implementation of flexible adaptation pathways. One is the cultural bias towards 'toughness', with fast rebuilding preferred to retreat in high-risk areas. It follows the instability of political systems changing with every mandate (usually on a 4–5 year interval), whereas adaption processes, and the implementation of protective measures such as levees or new building codes, take decades. Another barrier is the fact that adaptation requires reliable financing schemes, which are difficult to guarantee over long time periods. Finally, the institutional fragmentation that characterizes rebuilding and adaptation efforts — a process spread over different government layers, such as city, state and federal levels — has hindered a regionally focused approach. Such an approach is needed to ensure that the implemented solutions are consistent — for example, the design of city building code policies should be compatible with federal flood insurance regulations.

Using existing methods, Rosenzweig and Solecki identify three critical dimensions — multidimensionality, interdependency and intertemporality — that should be integrated into both the research and the practice needed to develop flexible adaptation pathways, and how these have been addressed in NYC[7,8]. Multidimensionality means the city acknowledges that climate adaptation is not a separable policy, but it is integrated into other policies, such as public health and developing green buildings. Interdependency refers to coordinating adaptation across spatial scales, sectors and jurisdictional boundaries. Intertemporality refers to the dynamics of adaptation, which evolves over time, and requires indicators and monitoring systems that incorporate the most recent risk information to evaluate investments.

Why promote guidelines for flexible pathways at the city level? Rosenzweig and Solecki show cities are not only in the frontline of suffering climate-related impacts, but also provide first aid to solve the problems. Cities have a long experience in addressing multiple environmental stresses (water supply, waste disposal and air quality), and climate change is now added to the equation. By forming networks, such as C-40 Cities (http://www.c40.org/) and Connecting Delta Cities (http://www.deltacities.com/home), cities can learn best practices from each other, and communicate with state- and federal-level governments about the need for climate preparedness.

Implementing the flexible adaptation pathways as sketched by Rosenzweig and Solecki is only viable through a cooperation of scientists and other stakeholders that provide adequate risk information to policy. Under the pressure of rebuilding NYC after Hurricane Sandy, much has been achieved in this respect. The key questions now are how to maintain flexibility in policy, how to fund adaptation and how to constantly work on the science–policy interface, without needing another disaster to trigger action? ❐

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SOIL CARBON

Resisting climate change

Increasing temperatures are expected to increase decomposition rates in soils, potentially reducing ecosystem carbon storage. Research now indicates that — in a tropical montane forest — soil carbon stocks are unaffected by higher temperatures despite substantially increased rates of CO_2 release from the soil.

Iain P. Hartley

Soils contain more carbon than the atmosphere and all plant biomass combined. In short-term experiments (~1–10 years duration), warming has been shown to increase the rate at which this carbon is released from soils to the atmosphere. Therefore, as global temperatures increase, there are fears that more CO_2 may be released to the atmosphere, further increasing temperatures, which in turn could result in more CO_2 being released from soils, and so on. Writing in *Nature Climate Change*, Giardina *et al.*[1] report that they have tested this important theory by investigating how soil carbon stocks changed with temperature along an altitudinal gradient on the eastern slope of the Mauna Kea volcano in Hawaii. Across this gradient, the tree species and soil type were relatively constant, providing an excellent opportunity to investigate how temperature affects soil carbon storage.

Their results suggest that, while the initial stages of decomposition do indeed proceed faster in the warmer sites, this does not translate to any clear reduction in soil carbon stocks (Fig. 1). Furthermore, based on radiocarbon dating, Giardina *et al.*[1] suggest that the lack of a change in soil carbon stocks is not simply caused by greater rates of soil organic matter decomposition in warmer soils being balanced out by greater soil carbon inputs from these more productive forests. The average age of the organic matter — which provides an indication of how quickly carbon cycles through a soil, referred to as its residence time — was not related to either temperature or forest productivity. Therefore, it seems that, across this altitudinal gradient, another factor is playing a more important role in controlling the amount of carbon stored in the soil.

The study[1] investigates one of the most fundamental and unresolved questions in terrestrial carbon cycle research: how is the amount of carbon stored in soils controlled? There have been calls for a paradigm shift in the way in which soil organic matter dynamics are studied[2]. Historically, a lot of emphasis has been placed on investigating the chemistry of the organic matter itself, but there is growing recognition that processes within soils that protect organic matter from decomposers are more important in controlling the amount of carbon stored[2]. For tropical soils, the concentration of key iron and aluminium minerals in the soil may be particularly important, because they can bind with organic matter and protect it from decomposition[3]. In the current study, the turnover of the organic matter correlated strongly with the concentration of key aluminium-containing minerals, indicating that the mineralogy of the soils may be the key determinant of decomposition rates and carbon storage. The authors argue that the organic matter in these soils is bound strongly by the minerals and is therefore effectively unavailable to decomposers, and that this explains why soil carbon stocks are unrelated to temperature across this gradient.

On the other hand, because carbon storage and turnover rates in these soils were not correlated with productivity, with a 50% increase in carbon inputs having no clear effect on soil carbon storage, the results also suggest that the mineral surfaces may have become saturated and that the soils are now unable to protect further carbon inputs. This is important because, at present, terrestrial ecosystems are absorbing up to one-third of the CO_2 that humankind releases into the atmosphere, with this being considered to be due to higher atmospheric CO_2 concentrations increasing plant productivity. While much of the uptake may be due to increasing carbon storage in plant biomass[4], if there is an upper limit to the amount of carbon these tropical soils can store, then this may reduce the capacity of these ecosystems to provide the key service of climate change mitigation.

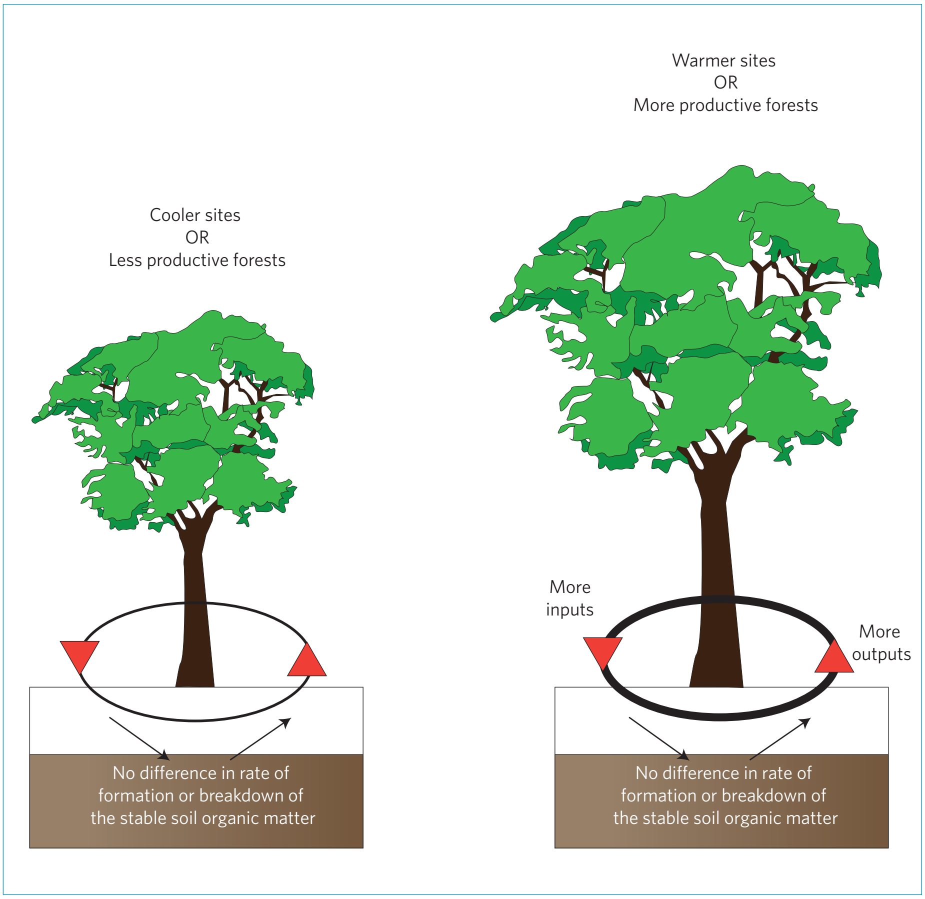

Figure 1 | Schematic indicating how carbon may cycle through tropical montane forest soils in Hawaii. Giardina *et al.*[1] show that there are more carbon inputs to the soils, and more carbon dioxide release from soil surface, at the warmer sites. However, they argue that carbon storage is unaffected because it is controlled more by the properties of the soils themselves.

Giardina *et al.*[1] caution against extrapolating their findings beyond the study area, not least because of how geographically variable soils are. Reflecting this challenge, a recent study in central Europe, which measured topsoil carbon stocks in over 500 soil profiles, found that, for a given amount of fine-grained particles in a soil — which is often used as a proxy for potential mineral protection of organic matter[2,5] — soil carbon storage was lower at warmer sites[6]. Thus, in temperate soils, there may be the potential for global warming to reduce soil carbon storage, albeit the rate of any carbon release remains highly uncertain. Combining results based on well-constrained temperature gradients, such as that studied by Giardina *et al.*[1], with big multisite datasets (as in ref. 6) may help advance understanding of how climatic factors, soil mineralogy and other soil properties interact to control carbon storage in different geographical areas.

In summary, the results presented by Giardina *et al.*[1] indicate that in Hawaii, soil mineralogy is a much stronger predictor of soil carbon storage than either temperature or forest productivity. It seems that the majority of the organic matter in these soils is tightly bound to mineral surfaces, reducing the potential magnitude of any carbon release as temperatures increase. On the other hand, it also appears that these mineral surfaces may now be saturated with organic matter. Therefore, as atmospheric CO_2 concentrations and soil carbon inputs increase, these new inputs may remain unprotected from decomposers, reducing the potential for additional carbon storage in these soils. Overall, soil carbon stocks in these tropical montane forests may be largely unaffected by global change, even if temperatures and atmospheric CO_2 concentrations increase substantially. ❐

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