low temperatures, so that the caesium atoms formed an exotic state of matter known as a Bose–Einstein condensate (BEC), whereas the lithium atoms instead formed a quantum gas called a Fermi gas.

The direct interaction between the caesium atoms was weakly repulsive, whereas the direct interaction between the caesium and lithium atoms could be tuned to be either attractive or repulsive. There was no direct interaction between the lithium atoms because of a fundamental principle of quantum mechanics that states that two fermions cannot occupy the same space. This principle also meant that the lithium gas had a much larger volume than the BEC of caesium atoms, which was located at the centre of the gas. DeSalvo *et al.* demonstrated that the presence of the lithium gas had two effects on the caesium BEC.

First, when the BEC was set to oscillate back and forth in the harmonic trap, the oscillation frequency changed when the lithium gas was present. The reason for this change is that the energy of the caesium atoms was shifted by the direct interaction between the caesium and lithium atoms. This energy shift was spatially dependent because the density of the lithium gas decreased as a function of distance from the centre of the trap. As a result, the BEC was subjected to an additional trapping potential from the lithium gas that altered the oscillation frequency.

The second, and arguably more intriguing, effect was that the lithium gas made the BEC decrease in size. By carefully analysing their experimental data, DeSalvo and colleagues concluded that this effect was caused by an attractive interaction between the caesium atoms that was mediated by the lithium gas. The results were in fair agreement with theoretical predictions based on a type of interaction called a Ruderman–Kittel–Kasuya–Yosida (RKKY) interaction, which has been shown[4–6] to exist as an interaction mediated by a Fermi gas precisely like the lithium gas.

RKKY interactions give rise to a great variety of magnetic phenomena in rare-earth elements — the collective name for 17 chemically similar metallic elements — in which electrons play the part of the Fermi gas. In addition, electronic devices, such as hard drives, that exploit a phenomenon known as the giant-magnetoresistance effect contain magnetic layers that are thought to be coupled by RKKY-like interactions[7].

Although the observed mediated interaction between the caesium atoms was quite weak, DeSalvo *et al.* used a clever trick to show that it could still have spectacular effects. The authors tuned the direct interaction between the caesium atoms to be only very weakly repulsive so that the attractive mediated interaction was comparatively stronger. The combination of the direct and mediated interactions then gave rise to a net attraction between the caesium atoms. Because, unlike for fermions, nothing prevents bosons from occupying the same space, the BEC collapsed. The authors observed this collapse through the formation of small, soliton-like blobs of caesium atoms — solitons are spatially localized states that are characteristic of BECs.

Given the unrivalled versatility of atomic gases, DeSalvo and colleagues' results open up the possibility of exploring mediated interactions in detail and probing interactions that have never been seen before. So far, only a weak mediated interaction has been observed, and it would be useful to study stronger interactions. Such interactions should greatly affect the energy spectrum of excitations of the BEC[8] and give rise to a range of exotic phases of matter in mixtures of bosons and fermions[9,10].

Future work should also explore the reciprocal case of an interaction between fermions that is mediated by a BEC. This mediated interaction is, in general, much stronger than the fermion-mediated interaction because of the large compressibility of a BEC compared with a Fermi gas, and it could also lead to previously unobserved phases of matter[11–13]. It will be exciting to see what discoveries follow the breakthrough results of DeSalvo and colleagues. ■

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1. Weinberg, S. *The Quantum Theory of Fields* (Cambridge Univ. Press, 1995).
2. Schrieffer, J. R. *Theory of Superconductivity* (Perseus, 1999).
3. DeSalvo, B. J., Patel, K., Cai, G. & Chin, C. *Nature* **568**, 61–64 (2019).
4. Ruderman, M. A. & Kittel, C. *Phys. Rev.* **96**, 99–102 (1954).
5. Kasuya, T. *Prog. Theor. Phys.* **16**, 45–57 (1956).
6. Yosida, K. *Phys. Rev.* **106**, 893–898 (1957).
7. Grosso, G. & Parravicini, G. P. *Solid State Physics* 2nd edn (Elsevier, 2013).
8. Kinnunen, J. J. & Bruun, G. M. *Phys. Rev. A* **91**, 041605 (2015).
9. Büchler, H. P. & Blatter, G. *Phys. Rev. Lett.* **91**, 130404 (2003).
10. Sachdev, S. *Nature Phys.* **4**, 173–185 (2008).
11. Heiselberg, H., Pethick, C. J., Smith, H. & Viverit, L. *Phys. Rev. Lett.* **85**, 2418–2421 (2000).
12. Bijlsma, M. J., Heringa, B. A. & Stoof, H. T. C. *Phys. Rev. A* **61**, 053601 (2000).
13. Camacho-Guardian, A. & Bruun, G. M. *Phys. Rev. X* **8**, 031042 (2018).

BIODIVERSITY

A mountain of ecological interactions

A detailed biological assessment of Africa's highest mountain explores how climate modulates the effects of human land use on plants, animals, microorganisms and a diverse array of ecosystem functions. SEE LETTER P.88

ROBERT M. PRINGLE

Mountains support roughly one-third of all land-dwelling species and supply water for nearly half of all people[1]. The ecology of mountain environments is strongly influenced by climate[2–4]. For example, because temperatures drop as altitude increases, organisms that have greater cold tolerance are favoured at higher elevations. Accordingly, there is a rapid change in the species present as one moves up a mountain from the warm lowlands to the cold highlands. And because few organisms can withstand the most-extreme conditions, the total number of species tends to be low on mountaintops.

Climate change is now rearranging the pieces of this puzzle[5,6], and ecologists are struggling to predict the picture that will emerge[7,8]. One major source of uncertainty is the extent to which the effects of human land use (activities such as farming and logging) might interact with climatic factors to shape the distribution of species and the operation of biogeochemical processes. On page 88, Peters *et al.*[9] report their analysis of an astonishingly comprehensive ecological data set from Mount Kilimanjaro (Fig. 1), which shows that temperature and rainfall modulate the effects of human land use on biodiversity and ecosystems.

A previous study[10] from the same research group revealed that the number of plant and animal species declines at an almost linear rate as elevation increases on Mount Kilimanjaro, suggesting that temperature is the main determinant of species richness. Peters *et al.* have expanded the scope and scale of that earlier assessment. Their new study reports data gathered over 6 years by 50 researchers at 60 sites ranging from 866 to 4,550 metres above sea level. These sites represented both natural habitats, such as lowland savannahs and alpine heaths, and habitats that had been heavily affected by human activity, including cropland and logged forests. The authors noted the number of species of plants, animals and soil-dwelling bacteria at each study site. They also recorded data for 30 different ecosystem functions, which are processes related to the transfer of energy and matter through the system (for example, the rates at which plants grow, organic matter decomposes and greenhouse gases are emitted).

To convert human impacts into a common currency for use in statistical analyses, Peters *et al.* devised a quantitative metric of land-use intensity, which integrated information about several types of human disturbance. To assess climate, they monitored the average annual temperature and rainfall at each site. Researchers studying large-scale ecological phenomena are often forced to gather previously published data from disparate sources and stitch this information together for analysis, which can introduce biases and artefacts. By instead measuring a wide range of attributes in many places using standardized methods, Peters and colleagues were able to paint one of the most detailed ecological portraits achieved thus far for any mountain.

Peters *et al.* report that the combined effects of climate and human land use manifested in a consistent way for both plants and animals. Species richness hardly differed between natural and human-altered habitats at high elevations, but species richness was reduced in the low-elevation habitats that had been transformed by human activity. These trends were best described by statistical models that included interactions between climate and land-use intensity — in other words, the effects of land use were dependent on climate, and the interplay of both these factors was necessary to explain the patterns observed in the data.

The trends in ecosystem functions in relation to climate and human activity are harder to decipher. All but five of the functions studied were affected by land-use intensity, and in most cases the effects of land use depended on climate. But these interactions exhibited all manner of forms, defying attempts to identify a general pattern. A clearer picture emerged when Peters and colleagues amalgamated all 30 of the ecosystem functions into a composite statistical index: overall, ecosystem functioning was more heavily affected at sites with greater land-use intensities, and these effects were stronger at low and high elevations than at intermediate elevations.

Ecologists yearn for simple rules to describe how ecosystems respond to environmental gradients and to perturbations arising from human activity. Yet analysing such complex systems, with their multitude of interwoven parts, requires a level of statistical abstraction that makes it difficult to discover the fundamental mechanisms underlying the patterns in the data. Peters and colleagues have unveiled a rich tapestry of ecological patterns on Mount Kilimanjaro, but explaining why those patterns are shaped by climate and land use in the ways that they are stands as a non-trivial challenge for future investigation.

As with any large-scale comparative analysis, one must also consider potential alternative explanations for the results. For example, on Mount Kilimanjaro, areas higher than 1,800 metres above sea level are part of a national park, and this designation places constraints on human land use. Indeed, Peters and colleagues found that land-use intensity was greatest at low elevations (and therefore positively correlated with temperature) across the mountain, which is typical for mountains worldwide[11]. These correlations make it difficult to fully disentangle the roles of climate and land use. Is it possible that human impacts were greatest at low elevations simply because human activity was much higher outside the national park?

CHERYL-SAMANTHA OWEN/NPL

Figure 1 | A field of maize (corn) in the shadow of Mount Kilimanjaro, Tanzania. Peters *et al.*[9] report a study of sites at different elevations on Mount Kilimanjaro in which they investigated how climate regulates the effects of human land use (such as maize farming) on ecosystems.

"The authors were able to paint one of the most detailed ecological portraits achieved thus far for any mountain."

To address this question, the authors carried out more analyses on different subsets of their data, which reinforced their original conclusions. Nevertheless, further work will be needed to establish the degree to which variation in human impacts at different elevations is governed by biophysical mechanisms, as opposed to reflecting trends in human behaviour that stem from both climatic and legal restrictions on land use.

As mountain environments heat up in a warming world, what can be done to safeguard their great biological wealth? Neither climate change nor human pressure on mountains will stop any time soon, but areas can be protected from intensive land use, and that can make a difference. Peters and colleagues' results indicate that such protection would need to span a range of elevations, from the low-lying sites that are currently most vulnerable to human impacts to the highland areas that will provide future homes for refugee species moving upslope. Nearly 40% of all mountain ranges lack any strictly protected nature reserves, and vanishingly few have conservation areas that span the entirety of their elevation[12]. There is an urgent need to expand the world's protected areas to achieve better coverage of elevation gradients[13]. ■

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1. Körner, C. *Ambio Spec. Rep.* **13**, 11–17 (2004).
2. Janzen, D. H. *Am. Nat.* **101**, 233–249 (1967).
3. McCain, C. M. & Grytnes, J.-A. *eLS* https://doi.org/10.1002/9780470015902.a0022548 (2010).
4. Polato, N. R. *et al. Proc. Natl Acad. Sci. USA* **115**, 12471–12476 (2018).
5. Morueta-Holme, N. *et al. Proc. Natl Acad. Sci. USA* **112**, 12741–12745 (2015).
6. Fadrique, B. *et al. Nature* **564**, 207–212 (2018).
7. Colwell, R. K., Brehm, G., Cardelús, C. L., Gilman, A. C. & Longino, J. T. *Science* **322**, 258–261 (2008).
8. Elsen, P. R. & Tingley, M. W. *Nature Clim. Change* **5**, 772–776 (2015).
9. Peters, M. K. *et al. Nature* **568**, 88–92 (2019).
10. Peters, M. K. *et al. Nature Commun.* **7**, 13736 (2016).
11. Nogués-Bravo, D., Araújo, M. B., Romdal, T. & Rahbek, C. *Nature* **453**, 216–219 (2008).
12. Elsen, P. R., Monahan, W. B. & Merenlender, A. M. *Proc. Natl Acad. Sci. USA* **115**, 6004–6009 (2018).
13. Pringle, R. M. *Nature* **546**, 91–99 (2017).

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