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BIODIVERSITY

Recovery as nitrogen declines

Pollution from atmospheric nitrogen deposition is a major threat to biodiversity. The 160-year-old Park Grass experiment has uniquely documented this threat and demonstrated how nitrogen reductions lead to recovery. SEE LETTER P.401

DAVID TILMAN & FOREST ISBELL

Although greater availability of a scarce nutrient might seem beneficial for all plant species, this is not so. Even in seemingly pristine and protected ecosystems, large losses of plant diversity can be caused by the addition of a nutrient that limits plant growth[1]. One documented example is the effect of deposition on land of nitrogen that was released into the atmosphere by fossil-fuel combustion and agriculture. However, it has been unclear whether plant diversity will recover when nitrogen emissions are reduced or whether additional restoration practices are required. On page 401 of this issue, Storkey *et al.*[2] use the unparalleled long-term data of the Park Grass experiment to show that plant diversity recovers as nitrogen deposition decreases.

The Park Grass experiment at Rothamsted Research in Harpenden, UK, was started in 1856 and is the longest-running study of grassland in the world (Fig. 1). By comparing fertilized and control (never fertilized) plots, the authors observed that plant diversity declined to about 30% of its original level during 135 years of nitrogen fertilization, but returned to about 70% of its original level two decades after fertilization was halted. Moreover, plant diversity declined in unfertilized control plots to about 50% of its original level as atmospheric nitrogen deposition increased from 1950 to 1985. Then, when the introduction of cleaner technologies greatly decreased nitrogen deposition from 1985 to 2012, plant diversity increased to about 80% of its original level. In both recoveries, plant communities tended to regain their former species compositions.

ROTHAMSTED RESEARCH

Figure 1 | The Park Grass experiment. This field experiment in Hertfordshire, UK, has been running since 1856. Its division of plants into control or treated plots has been used to test the effects of various interventions on agricultural productivity, such as fertilization and altered soil pH. Storkey *et al.*[2] used data from the experiment to document declines in plant biodiversity in response to nitrogen accumulation, but also found that diversity recovers as nitrogen levels decrease.

These observations contrast with results of a grassland experiment in Minnesota in which little, if any, recovery had occurred two decades after cessation of high rates of nitrogen fertilization[3]. Storkey and collaborators suggest the intriguing possibility that this difference is due to the fact that the Park Grass plots have been hayed (the grass cut, dried and removed) twice each year since the experiment started, whereas the Minnesota plots were never hayed. Why might this matter? Haying removes biomass and its nitrogen. If not removed, excess nitrogen that had accumulated in an ecosystem would recycle within that system, thereby retaining its ecological impacts long after nitrogen addition slowed or ceased.

Park Grass hay contains 1.5–2% nitrogen (see Fig. 2 of the paper[2]), and so annual removal of around 2 and 5 tonnes per hectare of hay from the control and fertilized plots, respectively, probably removed around 35 and 90 kilograms of nitrogen per hectare per year. This removal occurred alongside a reduction in nitrogen deposition of around 25 kg ha^{-1} yr^{-1} from its peak, for the control plots, and of an additional reduction of 96 kg ha^{-1} yr^{-1} for the plots that stopped receiving fertilizer. The removals of nitrogen through haying possibly hastened the plots' recovery.

The reason why increased availability of limiting nutrients can cause biodiversity losses lies in the evolutionary trade-offs that cause species to be specialists. Adaptations that increase the ability of a given plant species to compete for one limiting resource come at a cost to the species' capacity to deal with limitation by another resource or factor[4]. Thus, an increased supply of one resource should lead to the competitive displacement of those species that are superior competitors for the enriched resource, because they are among the poorer competitors for the new limiting factor. In theory, if enrichment led to accumulation of a formerly limiting nutrient, both cessation of its addition and decreases in its stores would be needed for that nutrient to again become limiting and for biodiversity to begin recovering.

Although further tests are needed to confirm that haying helped the Park Grass plots' recovery, the idea is supported by several other examples. Human activities release more available nitrogen and phosphorus than all natural terrestrial processes combined[5–8], and accumulation of these nutrients can cause dramatic shifts in species compositions and biodiversity in terrestrial and aquatic ecosystems. For instance, high-diversity heathlands in the Netherlands and Germany were replaced by low-diversity grasslands as nitrogen deposition reached higher rates than those in Britain[9,10]. Successful restoration of these heathlands often required physical removal of both vegetation and topsoil[11–14]. Similarly, 40 square kilometres of vegetable farmland in south Florida became a virtual monoculture of Brazilian pepper trees after it became part of Everglades National Park and agriculture ceased in 1975. Attempts to restore the pre-agricultural ecosystem were futile until both the invasive trees and the fertilized agricultural soil were removed[15–17]. For phosphorus-limited lake ecosystems, reduction of phosphorus inputs can be insufficient for lake recovery if excess phosphorus inputs from agriculture are retained and recycled[18].

These cases suggest that both reduction of nutrient inputs and removal of any large stores of accumulated nutrients may be required for restoration of native ecosystems. Some terrestrial restorations also require liming to overcome soil acidification, and seed addition when formerly abundant plant species are absent[2,11,13]. However, it is not yet clear how the magnitude of increases in nitrogen stores influences the recovery of grassland diversity after nitrogen addition decreases or ceases[3,19,20].

The insights from the Park Grass experiment, together with results from earlier studies, show that biodiversity can recover even after chronic high rates of nutrient pollution, and suggest that this recovery may be hastened by, or perhaps require, management practices that reduce accumulated nutrient stores. Moreover, it suggests that haying, a much gentler practice than destructive removal of both vegetation and soil, may reduce nutrient stores sufficiently to allow grassland diversity to recover. Finally, Storkey and colleagues' work demonstrates the great value that long-term studies can provide in identifying solutions to environmental problems. ■

David Tilman *and* **Forest Isbell** *are in the Department of Ecology, Evolution and Behavior, University of Minnesota, St Paul, Minnesota 55108, USA.* **D.T.** *is also in the Bren School of Environmental Science and Management, University of California, Santa Barbara.*
e-mails: tilman@umn.edu; isbell@umn.edu

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QUANTUM PHYSICS

Entanglement beyond identical ions

Control of quantum particles has been extended to enable different types of ion to be entangled — correlated in a non-classical way. This opens up opportunities for the development of new quantum technologies. **SEE LETTERS P.380 & P.384**

TOBIAS SCHAETZ

Entanglement is a peculiar phenomenon that causes two or more particles to share one common state, such that each particle can no longer be described independently. In this issue, Tan *et al.*[1] (page 380) and Ballance *et al.*[2] (page 384) report entangled pairs of ions consisting of two different atomic species — the first time that this has been achieved. They used the resulting systems to test the puzzling predictions of quantum mechanics with unprecedented accuracy. This in turn allowed them to benchmark trapped ions as an experimental platform for quantum technology, and to assess the platform's prospects to further exploit quantum effects for applications such as atomic clocks and quantum computation.

Quantum mechanics requires objects to be able to exist in two states simultaneously, even if the states are mutually exclusive. To picture such a superposition, imagine the magnetic needle of a hypothetical quantum compass pointing north and south at the same time. A measurement that determines the state of the needle will project it into one of its two possibilities at random — the result is not just unknown, but not determined before the measurement.

If there are two quantum magnetic needles, they can become entangled. For entangled objects, a measurement on one object that produces a completely random output instantaneously determines the potential result of the second object (or vice versa). The effect of the measurement is immediate and is independent of the distance between the objects.

Einstein was one of the founding fathers of the theory of quantum mechanics, but he and his colleagues realized that the consequences of entanglement severely violate intuition and logical conclusions based on the classical interpretation of nature. Einstein and others therefore proposed some seminal experiments[3] that could be used to show that their theory was far from complete. But because the practical

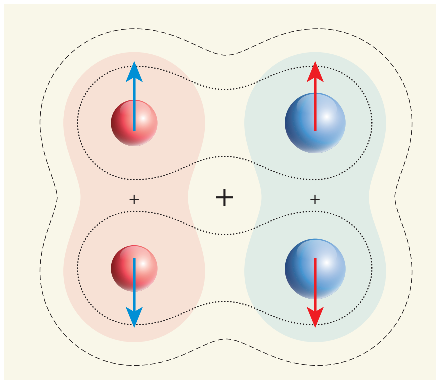

Figure 1 | Entangling two different ions. Individual ions can exist in one of two quantum 'spin' states: spin up (↑) and spin down (↓). Quantum mechanics also allows ions to form a superposition state (↑+↓) in which both the ↑ and ↓ states coexist. Tan *et al.*[1] and Ballance *et al.*[2] have prepared entangled pairs of ions consisting of two different atomic types — either different elements or different isotopes of an element. Each ion seems to be in a ↑+↓ state (shaded regions), but entanglement generates a correlated state (↑↑+↓↓, bounded by dashed lines; dotted lines indicate spin correlations), which means that a measurement of one of the two ions instantaneously affects the state of the other — that is, the two formerly independent ions have to be considered as a whole.

prerequisites for the experiments seemed to exceed the capabilities of any researcher, even in the future, they called their proposals *Gedankenexperimente* ('thought experiments').

Tan *et al.* and Ballance *et al.* report that quantum mechanics is accurate even when non-identical objects are entangled. Tan and colleagues entangled a beryllium-9 ion ($^{9}Be^{+}$) and a magnesium-25 ion ($^{25}Mg^{+}$), whereas Ballance and co-workers used two isotopes of calcium, $^{40}Ca^{+}$ and $^{43}Ca^{+}$. To describe how both groups created entanglement, consider the ions in each pair as magnetic needles that can point in one of two directions. This behaviour is analogous to that of a particle that has