

Solitary wave behaviour of sand dunes

Colliding dunes appear to traverse through one another and emerge unscathed.

Barchan sand dunes are highly mobile, crescent-shaped dunes that occur in areas where sand is sparse and the wind is unidirectional. Here we show mathematically how two such loose-grained dunes are able to pass through one another while still preserving their shape. The crucial parameters for this solitary-wave behaviour, which is consistent with field observations, are the heights of the two colliding dunes.

Because of their remarkable mobility, barchan dunes can disrupt structures such as roads and pipelines in arid, sandy regions. The velocity of a dune can reach several tens of a metres per year and is proportional to the reciprocal of its height¹, meaning that small dunes move faster than large ones^{1,2}. However, the dynamics and evolution of dunes are difficult to assess because of the large time scales involved, with field measurements having to be compiled over several decades²⁻⁴.

Several models have therefore attempted to describe dune morphology and formation⁵⁻¹⁰, for example in terms of the turbulent wind field, saltation sand flux¹ over the windward side, and avalanches travelling down the slip face. Calculations have focused on single dunes or on dune patterns, but not on dune interactions. We now solve the equations of motion that describe what happens when a small barchan dune bumps into a larger one. The results indicate that dunes can behave like solitons¹¹ under certain cir-



Figure 1 A field of crescent-shaped barchan sand dunes in the desert between Chimbote and Casma on the coast of Peru.

cumstances, crossing through one another without changing their shape. (Solitons conform to solutions of nonlinear equations, for example those that describe waves propagating in shallow water¹¹.)

This behaviour is consistent with the observed presence of small barchans on the downwind side of large ones¹², which seemingly indicates that they must have passed through one another without being altered. Small dunes are also found on the lee side of bigger ones in large barchan fields near Laâyoune, Morocco, and in the desert of La Pampa in Peru, for example (Fig. 1). The belief remains widespread, however, that a small barchan will be completely absorbed when it hits a bigger one, in view of the fact that a sand formation cannot cross the slip face of a dune without being destroyed.

We solved a set of equations^{7,8} describing a large heap of sand with the shape of a gaussian function, initially placed downwind of a smaller heap. The strength of the wind blowing into the system was fixed to a shear velocity of 0.5 m s^{-1} . After some time, the gaussians develop into a shape that is typical of barchan dunes¹⁰. The smaller barchan at some point bumps into the larger one, leading to a hybrid state in which the two dunes are fused in a complex pattern. Three different situations can be observed: coalescence, breeding and solitary-wave behaviour, depending on the relative sizes of the two dunes. As control parameters, we chose the relative difference in height between the two dunes, $\Delta h/h_2$, and the height of the smaller dune, h_2 .

The stability of the slip face of the upwind dune crucially influences the final state of the dunes leaving the hybrid state, as well as their relative velocities. When $\Delta h/h_2$ is small, the dunes move with similar velocities and solitary-wave behaviour occurs (Fig. 2). In the intermediate hybrid state, the dune behind is not sufficiently fast-moving to wander all of the way up to the slip face of the bigger dune in front, because it gains so much sand that at some point it becomes larger, and therefore slower, than the one in front. The dune that was previously bigger now becomes the smaller one, and its velocity becomes sufficiently large to leave the hybrid state. Effectively, it seems that the smaller dune crosses the bigger one, whereas in reality the two heaps never merge, owing to mass exchange.

For some values of h_2 and $\Delta h/h_2$, the emerging dune is larger than the incoming one; for other values, it is smaller. This means that they do not behave exactly as solitons, but rather like solitary waves. Intermediate values of h_2 and $\Delta h/h_2$ exist for which the two dunes exactly maintain their sizes and volumes — that is, they behave as solitons.

For smaller $\Delta h/h_2$, we find two different situations. If the height difference between the two dunes is very large, the small dune is entirely swallowed. For moderate height differences, we observe 'breeding' — the creation of two baby dunes at the horns of a barchan.

In regions where the wind is unidirectional and sand is abundantly available, another type of dune forms: these are known as transverse dunes and are translationally invariant. Solitary-wave behaviour should also be possible for transverse dunes. The interaction of laterally shifted dunes needs to be investigated and the behaviour of entire dune fields simulated.

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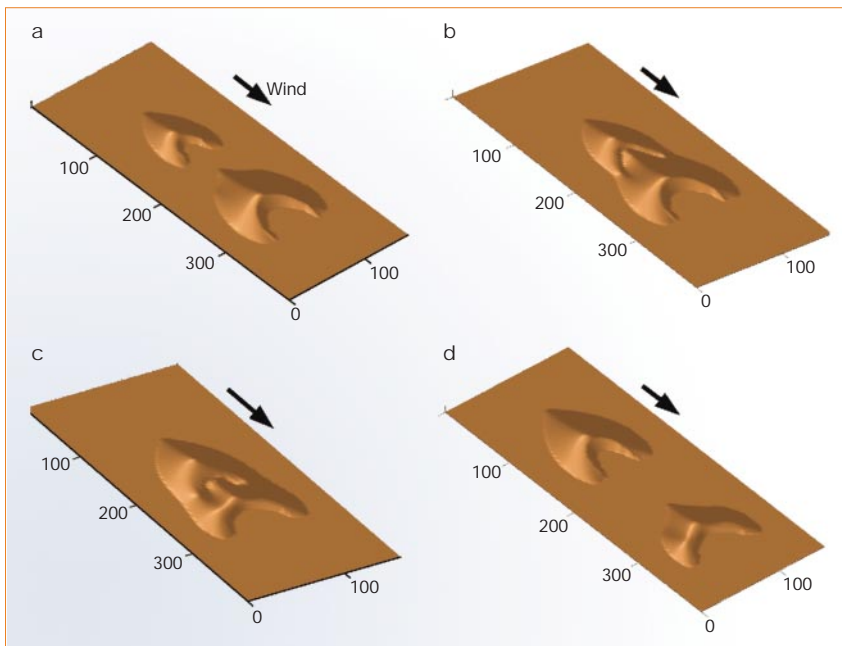


Figure 2 Time series of the solitary-wave behaviour of two barchan sand dunes placed one in front of the other. Parameters are $h_2 = 7.5 \text{ m}$ and $\Delta h/h_2 = 0.9$; distances are in metres. **a**, The dunes in their characteristic forms; **b**, 0.48 years after **a**, the smaller dune bumps into the larger one; **c**, hybrid state 0.63 years after **a**; **d**, the two dunes depart from the hybrid state (1.42 years after **a**).

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Genetics

Influence of TOR kinase on lifespan in *C. elegans*

The group of enzymes known as TOR (for ‘target of rapamycin’) kinases regulates cell growth and proliferation in response to nutrients and hormone-dependent mitogenic signals^{1,2}. Here we show that TOR deficiency in the nematode *Caenorhabditis elegans* more than doubles its natural lifespan. This new function for TOR signalling in ageing control may represent a link between nutrition, metabolism and longevity.

In *C. elegans*, the absence of LET-363/TOR activity causes developmental arrest at the L3 larval stage³. We examined nematodes bred as *let-363/CeTor* genetic null mutants and nematodes that had been depleted of TOR by using RNA interference to block *let-363* expression (termed *let-363*-RNAi worms), and found that these animals had a strikingly extended mean lifespan (Fig. 1a, squares and triangles, respectively). At 25.5 °C, the mean lifetime was 25 days in *let-363* mutants compared with 10 days in wild-type animals. This is all the more intriguing in light of the fact that TOR-deficient worms existed as arrested L3 larvae. In comparison, L3 larval arrest induced by starvation persisted for only 14 days on average in wild-type animals (Fig. 1a, diamonds).

Strong inhibition of mitochondrial respiration also arrests development at the L3 stage, whereas weaker inhibition permits growth to adulthood and extends adult lifespan, but only if it occurs during larval development⁴. In contrast, treatment with *let-363* double-stranded RNA starting from the first day of adulthood lengthens lifespan to a comparable extent when RNAi treatment is initiated at hatching (Fig. 1a, open triangles). This indicates that TOR has a role in ageing control during adulthood and that the long-lived phenotype of *let-363*-RNAi adults cannot be explained by reduced mitochondrial activity.

Longevity in *C. elegans* is controlled hor-

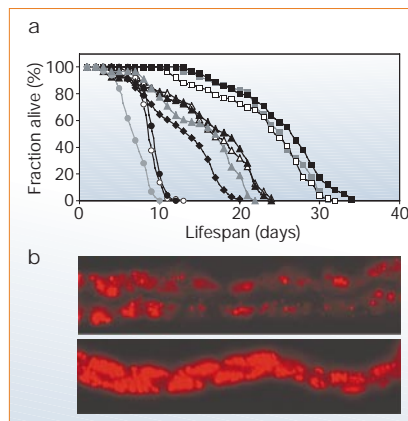


Figure 1 TOR deficiency in the nematode *Caenorhabditis elegans*. **a**, Lifespan of TOR-deficient worms compared with the wild type at 25.5 °C: wild type (filled circles); *daf-16(mg50)* (open circles); *dpy-5(e61) unc-13(e450)* double mutant (shaded circles); TOR-deficient triple mutants *let-363(h114) dpy-5(e61) unc-13(e450)* (open squares); *let-363(h111) dpy-5(e61) unc-13(e450)* (filled squares) and *let-363(h131) dpy-5(e61) unc-13(e450)* (shaded squares); *let-363*-RNAi-treated worms from hatching (open triangles) or from the first day of adulthood (shaded triangles); *let-363*-RNAi-treated *daf-16(mg50)* worms (filled triangles); starving-arrested wild-type L3 larvae (filled diamonds). Disruption of TOR by RNAi (triangles) seems to be incomplete, as lifespan is not extended as much as in *let-363* mutants (squares). **b**, Nile Red staining of lipid droplets in a wild-type L3 larva (top) and an L3 larva arrested by *let-363*-RNAi treatment (bottom). Images were obtained with the same exposure time.

monally by a conserved signalling pathway that involves insulin and insulin-like growth factor (IGF)^{5,6}. Mutants with reduced DAF-2/IGF signalling activity live twice as long as the wild type^{5,6}. The DAF-2/IGF cascade also acts during adulthood to influence ageing⁷. The remarkable similarity in the developmental stage at which ageing rate is affected, and our finding that the extended lifespan of *daf-2(e1370)* mutants is not increased further by treatment with *let-363* RNAi (results not shown) — as it is with RNAi blocking expression of respiratory-chain components⁴ — raise the possibility that TOR and the DAF-2/IGF pathway are related in controlling lifespan.

This idea is compatible with results indicating that the insulin/IGF cascade regulates protein synthesis and cell growth in mammals and *Drosophila* through the activity of nutrient-sensing TOR (reviewed in refs 1, 2, 8). We have also noted that *let-363*-RNAi animals share certain features of the pleiotropic *Daf-2*(-) phenotype, such as lipid accumulation mainly in intestinal cells⁹ (Fig. 1b), as well as reduced fertility¹⁰ (mean brood sizes: *let-363*-RNAi adults, 68 ± 6.4; wild type, 191 ± 14.5) and reduced viability¹⁰ (embryonic/early larval arrest: *let-363*-RNAi), 40.3%; wild type, 5.4%).

Strong mutations in DAF-2/IGF signalling cause a long-lived phenotype, together with a state of developmental diapause known as dauer that is triggered by starvation and crowding in the wild type¹¹. According to our results (not shown), *let-363(h111)* animals

bearing the thermosensitive *daf-2(e1370ts)* mutation were able to form dauers at the restrictive temperature. Furthermore, *let-363*-RNAi enhanced dauer formation in *daf-2(e1370)* animals. At 20 °C, only 4.6% (29 out of 630) of *daf-2(e1370)* mutants entered into the dauer stage, compared with 17.9% (146 out of 817) of *daf-2(e1370); let-363*-RNAi animals (results not shown). This indicates a genetic interaction between *let-363/CeTor* and *daf-2*. These results show that in *C. elegans* the TOR and DAF-2/IGF signalling pathways could be related in controlling ageing, metabolism and reproductive growth.

Lifespan extension in *daf-2(e1370)* mutants requires the activity of the forkhead transcription factor DAF-16 (refs 5, 6). Mutations in *daf-16*, however, do not suppress the long-lived phenotype of *let-363*-RNAi worms (Fig. 1a, filled triangles), indicating that TOR may be acting downstream or independently of DAF-16, and that it is interacting with the insulin endocrine system. Although the detailed signalling connections require clarification, our findings point to TOR as a possible mediator of lifespan regulation by insulin signalling and nutrient sensing.

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Metabolism

Ecology shapes bird bioenergetics

The basal rate of metabolism of birds and mammals is the lowest rate that is compatible with endothermic temperature regulation, balancing the heat generated with the heat lost by the product of thermal conductance and the temperature differential with the environment¹. Here I measure the bioenergetics of 13 species and 9 genera of birds of paradise (Paradisaeidae) and