23. Callaway, R. M. Are positive interactions species-specific? *Oikos* **82,** 202–209 (1998).
24. Choler, P., Michalet, R. & Callaway, R. M. Facilitation and competition on gradients in alpine plant communities. *Ecology* **82,** 3295–3308 (2001).
25. Archibold, O. W. *Ecology of World Vegetation* 280–318 (Chapman and Hall, London, 1995).
26. JMPin 4.0.2 (SAS Institute Inc., Duxbury Press, Cary, North Carolina, 2000).

Supplementary Information accompanies the paper on *Nature*'s website (http://www.nature.com/nature).

Acknowledgements

We thank the National Center for Ecological Synthesis and Analysis, The National Geographic Society, the Civilian Research and Development Foundation, and the Andrew W. Mellon Foundation for financial support.

Competing interests statement

The authors declare that they have no competing financial interests.

Correspondence and requests for materials should be addressed to R.M.C. (e-mail: callaway@selway.umt.edu).

Consumer versus resource control of species diversity and ecosystem functioning

Boris Worm*†, Heike K. Lotze*†, Helmut Hillebrand‡ & Ulrich Sommer†

* *Biology Department, Dalhousie University, Halifax, Nova Scotia, B3H 4J1, Canada*
† *Section of Marine Ecology, Institute for Marine Science, Kiel University, Düsternbrooker Weg 20, 24105 Kiel, Germany*
‡ *Erken Laboratory, Department of Limnology, Uppsala University, Norr Malma 4200, 76173 Norrtälje, Sweden*

A key question in ecology is which factors control species diversity in a community[1–3]. Two largely separate groups of ecologists have emphasized the importance of productivity or resource supply, and consumers or physical disturbance, respectively. These variables show unimodal relationships with diversity when manipulated in isolation[4–8]. Recent multivariate models[9–10], however, predict that these factors interact, such that the disturbance–diversity relationship depends on productivity, and vice versa. We tested these models in marine food webs, using field manipulations of nutrient resources and consumer pressure on rocky shores of contrasting productivity. Here we show that the effects of consumers and nutrients on diversity consistently depend on each other, and that the direction of their effects and peak diversity shift between sites of low and high productivity. Factorial meta-analysis of published experiments confirms these results across widely varying aquatic communities. Furthermore, our experiments demonstrate that these patterns extend to important ecosystem functions such as carbon storage and nitrogen retention. This suggests that human impacts on nutrient supply[11] and food-web structure[12,13] have strong and interdependent effects on species diversity and ecosystem functioning, and must therefore be managed together.

The most striking feature of life on Earth is its diversity. Consequently, the most fundamental question in ecology is which factors maintain diversity in ecological communities[2]. Here, we analyse the combined impacts of consumers and nutrient resources on plant diversity. The supply of limiting resources, such as nutrients, controls primary productivity; that is, the rate of production of organic matter. On local scales, productivity and diversity are often unimodally related (Fig. 1a), such that peak diversity is observed at intermediate productivity[8]. Declining diversity at higher levels of productivity is thought to be due to competitive exclusion. Exclusion can be prevented by periodic mortality events, caused by consumers or physical disturbance[4,6,7]. These factors also show unimodal relationships with diversity (Fig. 1b). Because the effects of productivity, disturbance and consumption on diversity have been analysed separately, their interactions in nature have remained elusive. In an attempt to unify these patterns theoretically, one study explored how traditional Lotka–Volterra competition models respond to increases in productivity and disturbance frequency[9]. The study predicted that the effects of disturbance on diversity depend strongly on productivity, and vice versa (for details see Fig. 1c). Physical disturbance and consumer pressure were predicted to give similar patterns[9]. These ideas have been mathematically elaborated[10], using a spatial competition model[14], in which the environment consists of a large number of discrete patches, each of which can be empty or occupied by one out of n species. The model assumes a linear competitive hierarchy where species i ($1 \leq i \leq n$) would always exclude species j if $i < j$. Multi-species coexistence in this model depends on a trade-off between competitive ability and patch colonization rate c_i or extinction rate m_i (ref. 14). Productivity is assumed to enhance colonization rates of all species by a constant R and disturbance increases extinction rates of all species by a constant D (ref. 10). The dynamics of the proportion p_i of patches occupied by species i is represented as

$$\frac{dp_i}{dt} = c_i R p_i \left(1 - \sum_{k=1}^{i} p_k\right) - (m_i + D)p_i - \sum_{k=1}^{i-1} c_k R p_k p_i \qquad (1)$$

$$(i = 1, 2, \ldots, n)$$

where the first term represents colonization, the second local extinction and the third competitive exclusion[10]. Notably, predictions from this model are almost identical to those of earlier simulations[9,10]. Thus, general patterns emerged (Fig. 1c), despite the differences in model structure (spatial compared with non-spatial), assumptions (equilibrium versus non-equilibrium) and complexity.

We tested these models in a food-web context by experimentally manipulating consumer pressure (absent, present) and nutrient supply (no, low, medium, high nutrient enrichment; see Methods)

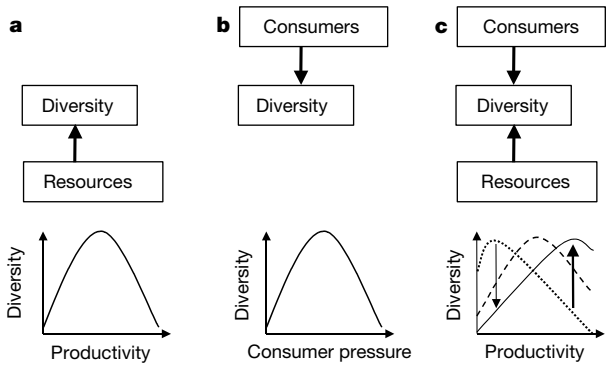

Figure 1 Consumer versus resource control of species diversity. **a**, **b**, Univariate models predict two independent relationships, where diversity peaks at intermediate resource supply or productivity (**a**), and at intermediate consumer pressure or physical disturbance (**b**), respectively[4,5,7,8]. **c**, Multivariate models[9,10] predict that the effects of consumers on diversity depend on resource supply and productivity; peak diversity shifts from low to intermediate to high productivity depending on whether consumer pressure is low (dotted line), intermediate (dashed line) or high (solid line). Consumers decrease diversity at low productivity (thin arrow) but increase diversity at high productivity (thick arrow).

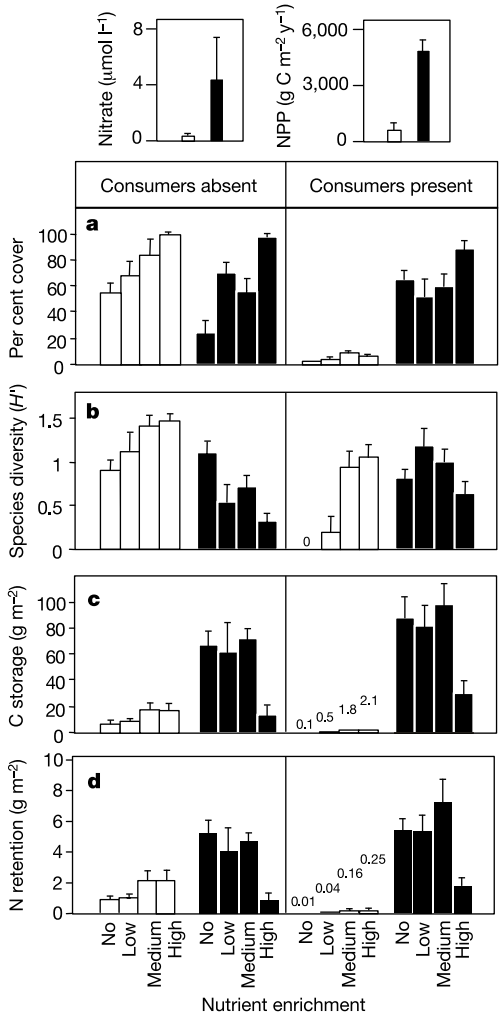

Figure 2 Factorial field experiments. Effects of consumers and nutrient enrichment on total cover (**a**), species diversity (**b**; Shannon Index (H')), carbon storage (**c**), and nitrogen retention (**d**). Open bars, Bald Rock; filled bars, Maasholm. Differences in yearly average nitrate concentrations and net primary productivity (NPP) between these sites are shown in the inserts above. All bars represent means ± 1 standard error ($n = 4$, except nitrate ($n = 10$) and NPP ($n = 8$)).

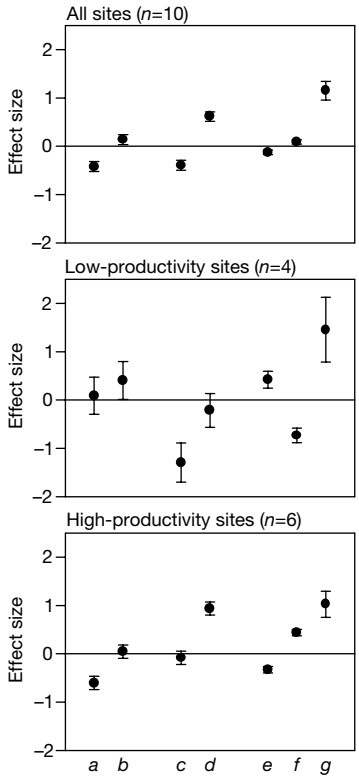

Figure 3 Factorial meta-analysis of published field experiments. Effects of nutrient enrichment on species diversity without (*a*) or with (*b*) consumers. Effects of consumers on species diversity without (*c*) or with (*d*) nutrient enrichment. Mean effects of nutrient enrichment (*e*), consumers (*f*), and consumer × nutrient interaction (*g*) on species diversity. Effect sizes are Hedges's *d* (see Methods) ± 95% confidence interval. A positive *d* indicates an increase; negative *d* a decrease in diversity, relative to controls. Effects are statistically significant ($P < 0.05$) if confidence limits do not overlap $d = 0$.

in two wave-sheltered rocky shore communities. At sheltered sites productivity is tightly linked to nutrient supply[15,16], and consumers are the chief source of mortality[17]. This is in contrast to wave-exposed shores where physical disturbance is more important[17]. We chose the two sites to test for consumer–nutrient interactions under contrasting conditions of background nutrient supply and productivity (see insert in Fig. 2). Our rationale was that to cover the full range of nutrient supply and productivity in nature we needed to combine small-scale experimental and large-scale environmental gradients. Bald Rock, Scotian shelf, northwest Atlantic, showed low nutrient supply and productivity ranged at the lower end of reported values for rocky shores[15], whereas Maasholm, Baltic Sea, had very high nutrient supply and productivity was comparable to maximum values in coral reefs[18].

Macroalgae were the main space colonizers in both experiments. Nutrient enrichment enhanced algal productivity, as indicated by significant increases in algal cover (Fig. 2a and Table 1). Increases in cover in nutrient-enriched plots tended to be less pronounced when

Table 1 Factorial analysis of variance

Source	d.f.	Per cent cover		Species diversity		Carbon storage		Nitrogen retention	
		F	*P*	*F*	*P*	*F*	*P*	*F*	*P*
Bald Rock									
Consumers	1	225.9	<0.001	66.3	<0.001	177.6	<0.001	132.8	<0.001
Nutrients	3	9.0	<0.001	22.5	<0.001	9.9	<0.001	6.9	0.002
C × N	3	2.7	0.068	5.3	0.006	0.1	0.966	1.7	0.193
Residual	24								
Maasholm									
Consumers	1	0.1	0.717	5.8	0.024	5.1	0.033	3.2	0.065
Nutrients	3	15.9	<0.001	3.9	0.021	12.7	<0.001	9.2	<0.001
C × N	3	5.1	0.007	3.0	0.051	0.5	0.714	0.5	0.797
Residual	24								

The effects of consumers, nutrient enrichment, and their interaction (C × N) on per cent cover, species diversity and ecosystem functioning in the two field experiments are shown. *F* statistics and *P*-values are shown. d.f., degrees of freedom.

consumers were present, as indicated by statistical interactions between the two factors (Table 1, note that this interaction is marginal in Bald Rock, $P = 0.068$). As predicted, changes in nutrient supply and consumer pressure had interactive effects on species diversity (Fig. 2b and Table 1). Furthermore, their main effects changed in sign between two sites of contrasting productivity (Fig. 2b). In Bald Rock, nutrient enrichment increased diversity and consumers decreased diversity. These effects were interactive: consumers had strong negative effects under ambient conditions, but weak effects under enriched conditions. In Maasholm, the reverse applied: nutrient enrichment decreased diversity and consumers increased diversity. Again, these effects were interactive: consumers reduced diversity under ambient conditions, but enhanced it under enriched conditions. Peak diversity was found in treatments without consumers in Bald Rock, but in treatments with consumers in Maasholm (Fig. 2b). Furthermore, in Maasholm peak diversity shifted to higher levels of nutrient enrichment when consumers were present.

Ecosystem functioning showed markedly similar responses to experimental manipulations as diversity. Rates of carbon storage and nitrogen retention increased with nutrient enrichment but decreased when consumers were present in Bald Rock (Fig. 2c, d and Table 1). In Maasholm these effects were reversed. Declining C storage and N retention in Maasholm was linked to the loss of long-lived species, such as perennial fucoid algae, which are replaced by fast-growing but short-lived annual algae and phytoplankton at higher levels of eutrophication[19]. The responses to enrichment in both experiments were highly nonlinear: in Maasholm little change in ecosystem functioning was seen in low and medium enrichment treatments, but marked decreases were seen under high nutrient loading (Fig. 2c, d). In Bald Rock, enrichment increased rates of C storage and N retention only from low to medium, but not from medium to high treatments (Fig. 2c, d). In both experiments, marked changes in ecosystem functioning coincided with a drop in diversity. Correlations between the treatment means of diversity and log-transformed ecosystem functioning revealed nonsignificant trends in Maasholm (C storage: $r = 0.76$, $P = 0.09$; N retention: $r = 0.78$, $P = 0.08$, $n = 8$) and highly significant relationships in Bald Rock (C storage: $r = 0.96$, $P = 0.01$; N retention: $r = 0.94$, $P = 0.01$, $n = 8$). Although theory suggests that this link is due to a general diversity–functioning relationship[2,20], this needs to be tested empirically by experiments that manipulate species diversity and composition independently.

We used factorial meta-analysis[21] to test whether these results are consistent across widely varying communities, including marine and freshwater phytoplankton, periphyton (benthic microalgae), macroalgae and salt marshes. We compiled diversity data from ten recent field experiments that manipulated consumers and nutrient supply in factorial combination (see Methods). When we pooled the data across all sites (Fig. 3, top panel), both the effects of nutrient enrichment and consumers on diversity changed from negative to positive depending on the presence of the other factor (Fig. 3; *a–d*). Overall, nutrient enrichment had slight negative effects, whereas consumers had slight positive effects on diversity (Fig. 3; *e*, *f*); however, a highly significant interaction term ($P < 0.001$) suggested that it is not informative to analyse these factors in isolation (Fig. 3; *g*). The positive term indicates a synergistic interaction: positive effects of nutrient enrichment on diversity were only realized when consumers were present and vice versa. The *Q*-test statistic suggested that the effect sizes were not homogenous ($P < 0.05$). To remove this underlying heterogeneity we split the data set into low-productivity and high-productivity sites (Fig. 3, middle and bottom panels). The results show that strong interactive effects among consumers and nutrients remain (Fig. 3; *g*), but their mean effects on diversity changed from positive to negative (nutrients, Fig. 3; *e*) and from negative to positive (consumers, Fig. 3; *f*) with increasing productivity ($P < 0.05$).

We conclude that multivariate models[9,10] and factorial experiments from different aquatic communities show the same striking patterns: the effects of nutrient enrichment depend on consumer pressure and vice versa. Both factors have strong and opposing effects on diversity, which change in sign among low-productivity and high-productivity ecosystems. When consumers are present, peak diversity shifts towards higher levels of nutrient supply. Moreover, our data suggest that these patterns extend to important ecosystem functions such as C storage and N retention. To our knowledge, the present study is the first where the interactive effects of consumers and resources on diversity and ecosystem functioning are shown at the same time. Three ecological theories are combined, one emphasizing resources, one emphasizing food-web interactions, and one emphasizing linkages between diversity and ecosystem functioning. This empirical and theoretical synthesis may provide a unifying concept of both causes and consequences of diversity.

These results have important implications for conservation of biodiversity and environmental management because they strongly suggest the potential for synergistic interactions among the most common human impacts on ecosystems. Human alterations of the nitrogen and phosphorus cycles continue to increase nutrient supply and productivity in terrestrial, freshwater and coastal ecosystems worldwide[11]. At the same time, consumer pressure is altered through overharvesting of herbivore and predator populations[12,13], habitat fragmentation[22] and destruction[23]. We conclude that it is not meaningful to assess or manage these impacts in isolation. Rapid change in species composition and loss of diversity will occur when the dynamic balance of consumer and resource control is distorted, especially when consumer removals and resource enrichment occur at the same time. Our data also suggest that such changes will compromise the ability of these systems to retain the excess carbon and nitrogen that is brought upon them by human activities. □

Methods

Field experiments

Experiments were run from February to December 1998 at Maasholm, Baltic Sea (54° 41.3′ N, 10° 0.5′ E), and from February to December 1999 at Bald Rock, Scotian shelf, northwest Atlantic (44° 28.3′ N, 63° 34.7′ W) at 0.8–1 m depth below mean water level. These sites had very similar physical characteristics and species pools[24], but represented opposite extremes in primary productivity (see inserts in Fig. 2). Both sites were colonized by perennial fucoid macroalgae, and a larger number of fast-growing annual macroalgae (for details see ref. 24). Consumers of algal biomass were gammarid amphipods, idoteid isopods and littorinid snails at both sites. We followed algal colonization on replicate granite rocks, collected at the experimental sites. Rocks were randomly assigned to 32 cages (25 × 25 × 25 cm), covered with a clear 1-mm polyethylene mesh. Photon flux in the cages was reduced by less than 8% (LICOR SA 192-A). Consumer pressure and nutrient enrichment were manipulated using a factorial 2 × 4 design with four replicates. Consumers were excluded from closed cages but had free access to open cages, which had one side cut open. Cages were brush-cleaned weekly and checked carefully for invading consumers. Nutrient enrichment was manipulated with diffusers filled with slow-release fertilizer[19,25]. We maintained four enrichment levels over the experimental period. These increased dissolved inorganic nitrogen by 0% (no), 8% (low), 38% (medium) and 150% (high) relative to background concentrations[25]. Species cover was assessed using a Plexiglas sampling frame with 50 randomly placed dots. Carbon and nitrogen storage in algal biomass was analysed at the end of the growing period. All biomass was scraped off, dried at 80 °C for 48 h, and dry mass was determined to the nearest mg. Samples were ground to powder and analysed for carbon and nitrogen content on an automated C:N analyser (Fisons Instruments, NA 1500 N). Statistical analyses were performed on per cent cover data collected in late summer, when the number of species peaked at our sites. Species diversity was computed from the cover data, using the Shannon Diversity Index $H' = -\sum_{i=1}^{k} \ln(p_i)p_i$, where p_i is the cover of species i divided by the total cover of k species. This index reflects species richness S (number of species), evenness ($H'/\log[S]$) and their intercorrelations, and is considered the best measure of their joint influence[26]. Expressing diversity as richness, however, gave the same patterns (data not shown). The interactive effects of consumers and nutrient enrichment were analysed by factorial fixed-factor analysis of variance (ANOVA). Per cent cover data were angular transformed and other data were $\log(x + 1)$-transformed to achieve homogeneity of variances.

Meta-analysis

Using a new factorial meta-analysis technique[21] we analysed ten field experiments that reported effects of consumers and nutrient supply on species diversity. Studies had to fulfil the following criteria: consumers and nutrient supply were manipulated in a well-replicated factorial design, species diversity (Shannon Index) or species density (species

per sample area) were measured as dependent variable and treatment means, sample sizes and variance estimates were reported. Included were two experiments on macroalgae (this study), five experiments with periphyton in freshwater, brackish and marine ecosystems[27,28], two experiments with salt marsh plants[29], and one with lake phytoplankton[30], including subtropical and temperate climates in North America and Europe. We analysed data from sampling dates when species richness reached the seasonal peak, which was usually in late spring or summer. Data were standardized using the common meta-analysis metric of standardized effect size, Hedges's *d* (ref. 21). This is a measure of the difference between experimental and control means, divided by a pooled standard deviation and multiplied by a correction factor to account for small sample sizes. Homogeneity of effect sizes was tested using the *Q*-statistic[21]. As we detected significant heterogeneity among effect sizes we split the data set into low-productivity (oligotrophic and mesotrophic) and high-productivity (eutrophic) sites, based on information provided in the publications.

Received 23 January; accepted 12 April 2002; doi:10.1038/nature00830.

1. Hutchinson, G. E. Homage to Santa Rosalia, or why are there so many kinds of animals. *Am. Nat.* **93,** 145–159 (1959).
2. Tilman, D. Causes, consequences and ethics of biodiversity. *Nature* **405,** 208–211 (2000).
3. Sommer, U. & Worm, B. (eds) *Competition and Coexistence* (Springer, Berlin, 2002).
4. Connell, J. H. Diversity in tropical rain forests and coral reefs. *Science* **199,** 1302–1310 (1978).
5. Tilman, D. *Resource Competition and Community Structure* (Princeton Univ. Press, Princeton, 1982).
6. Flöder, S. & Sommer, U. Diversity in planktonic communities: an experimental test of the intermediate disturbance hypothesis. *Limnol. Oceanogr.* **44,** 1114–1119 (1999).
7. Buckling, A., Kassen, R., Bell, G. & Rainey, P. B. Disturbance and diversity in experimental microcosms. *Nature* **408,** 961–964 (2000).
8. Kassen, R., Buckling, A., Bell, G. & Rainey, P. B. Diversity peaks at intermediate productivity in laboratory microcosms. *Nature* **406,** 508–512 (2000).
9. Huston, M. A. *Biological Diversity* (Cambridge Univ. Press, Cambridge, 1994).
10. Kondoh, M. Unifying the relationships of species richness to productivity and disturbance. *Proc. R. Soc. Lond. B* **268,** 269–271 (2001).
11. Vitousek, P. M. *et al.* Human alteration of the global nitrogen cycle: sources and consequences. *Ecol. Appl.* **7,** 737–750 (1997).
12. Pauly, D., Christensen, V., Dalsgaard, J., Froese, R. & Torres, F. Jr Fishing down marine food webs. *Science* **279,** 860–863 (1998).
13. Jackson, J. B. C. *et al.* Historical overfishing and the recent collapse of coastal ecosystems. *Science* **293,** 629–638 (2001).
14. Tilman, D. Competition and biodiversity in spatially structured habitats. *Ecology* **75,** 2–16 (1994).
15. Mann, K. H. Seaweeds: their productivity and strategy for growth. *Science* **182,** 975–981 (1973).
16. Nielsen, K. J. Bottom-up and top-down forces in tide pools: test of a food chain model in an intertidal community. *Ecol. Monogr.* **71,** 187–217 (2001).
17. Menge, B. A. & Sutherland, J. P. Community regulation: variation in disturbance, competition, and predation in relation to environmental stress and recruitment. *Am. Nat.* **130,** 730–757 (1987).
18. Sorokin, Y. I. *Coral Reef Ecology* (Springer, Berlin, 1995).
19. Worm, B., Lotze, H. K. & Sommer, U. Coastal food web structure, carbon storage and nitrogen retention regulated by consumer pressure and nutrient loading. *Limnol. Oceanogr.* **45,** 339–349 (2000).
20. Chapin, F. S. III *et al.* Consequences of changing biodiversity. *Nature* **405,** 234–242 (2000).
21. Gurevitch, J., Morrison, J. A. & Hedges, L. V. The interaction between competition and predation: a meta-analysis of field experiments. *Am. Nat.* **155,** 435–453 (2000).
22. Terborgh, J. *et al.* Ecological meltdown in predator-free forest fragments. *Science* **294,** 1923–1925 (2001).
23. Watling, L. & Norse, E. A. Disturbance of the seabed by mobile fishing gear: a comparison to forest clearcutting. *Conserv. Biol.* **12,** 1180–1197 (1998).
24. Lotze, H. K., Worm, B. & Sommer, U. Strong bottom-up and top-down control of early life stages of macroalgae. *Limnol. Oceanogr.* **46,** 749–757 (2001).
25. Worm, B., Reusch, T. B. H. & Lotze, H. K. *In situ* nutrient enrichment: methods for marine benthic ecology. *Internat. Rev. Hydrobiol.* **85,** 359–375 (2000).
26. Stirling, G. & Wilsey, B. Empirical relationships between species richness, evenness, and proportional diversity. *Am. Nat.* **158,** 286–299 (2001).
27. Hillebrand, H., Worm, B. & Lotze, H. K. Marine microbenthic community structure regulated by nitrogen loading and herbivore pressure. *Mar. Ecol. Prog. Ser.* **204,** 27–38 (2000).
28. Hillebrand, H. & Kahlert, M. Effect of grazing and nutrient supply on periphyton biomass and nutrient stoichiometry in habitats of different productivity. *Limnol. Oceanogr.* **46,** 1881–1898 (2001).
29. Gough, L. & Grace, J. B. Herbivore effects on plant species density at varying productivity levels. *Ecology* **79,** 1586–1594 (1998).
30. Proulx, M., Pick, F. R., Mazumder, A., Hamilton, P. B. & Lean, D. R. S. Experimental evidence for interactive impacts of human activities on lake algal species richness. *Oikos* **76,** 191–195 (1996).

Acknowledgements

We thank L. Gough, R. Karez, D. Kehler, I. Milewski, R. A. Myers, R. T. Paine and T. B. H. Reusch for comments, and J. Gurevitch for statistical advice. This work was funded by the German Research Council (DFG) and the German Ministry of Science and Education.

Competing interests statement

The authors declare that they have no competing financial interests.

Correspondence and requests for materials should be addressed to B.W. (e-mail: bworm@is.dal.ca).

A global analysis of *Caenorhabditis elegans* operons

Thomas Blumenthal*, Donald Evans*, Christopher D. Link†, Alessandro Guffanti‡, Daniel Lawson‡, Jean Thierry-Mieg§, Danielle Thierry-Mieg§, Wei Lu Chiu‖, Kyle Duke¶, Moni Kiraly¶ & Stuart K. Kim¶

* *Department of Biochemistry and Molecular Genetics, University of Colorado School of Medicine, Box B121, 4200 E. 9th Avenue, Denver, Colorado 80262, USA*
† *Institute of Behavioral Genetics, Box 447, University of Colorado, Boulder, Colorado 80309, USA*
‡ *The Sanger Centre, Wellcome Trust Genome Campus, Hinxton, Cambridge CB10 1SA, UK*
§ *Gene Network Laboratory, National Institute of Genetics, Mishima 411, Japan, and National Center for Biotechnology Information, Bethesda, Maryland, USA*
‖ *Department of Molecular Sciences and Technologies, Pfizer Global Research & Development—Ann Arbor, 2800 Plymouth Road, Ann Arbor, Michigan 48105, USA*
¶ *Departments of Developmental Biology and Genetics, Stanford University Medical Center, 279 Campus Drive, Stanford, California 94305, USA*

The nematode worm *Caenorhabditis elegans* and its relatives are unique among animals in having operons[1]. Operons are regulated multigene transcription units, in which polycistronic pre-messenger RNA (pre-mRNA coding for multiple peptides) is processed to monocistronic mRNAs. This occurs by 3′ end formation and *trans*-splicing using the specialized SL2 small nuclear ribonucleoprotein particle[2] for downstream mRNAs[1]. Previously, the correlation between downstream location in an operon and SL2 *trans*-splicing has been strong, but anecdotal[3]. Although only 28 operons have been reported, the complete sequence of the *C. elegans* genome reveals numerous gene clusters[4]. To determine how many of these clusters represent operons, we probed full-genome microarrays for SL2-containing mRNAs. We found significant enrichment for about 1,200 genes, including most of a group of several hundred genes represented by complementary DNAs that contain SL2 sequence. Analysis of their genomic arrangements indicates that >90% are downstream genes, falling in 790 distinct operons. Our evidence indicates that the genome contains at least 1,000 operons, 2–8 genes long, that contain about 15% of all *C. elegans* genes. Numerous examples of co-transcription of genes encoding functionally related proteins are evident. Inspection of the operon list should reveal previously unknown functional relationships.

In order to search the genome for mRNAs that contain SL2, we hybridized microarrays containing 17,817 predicted genes (94% of known and predicted genes) with probe enriched for SL2-containing mRNAs (see Methods). The results are presented in Fig. 1a. The line shows that the genes form three peaks, a peak of about 1,200 genes with very high SL2/poly(A)$^+$ ratios and two larger peaks with low SL2/poly(A)$^+$ ratios containing the remainder of the genes. As a positive control, we identified 319 genes that produce SL2-containing mRNAs on the basis of analysis of the sequence traces of cDNAs from the Y. Kohara laboratory (listed in Supplementary Information Table 1). Fig. 1a shows that most (84%) of these were among the SL2-enriched genes. Negative controls include 100 genes that are the first genes in the operons identified by the 100 highest SL2/poly(A)$^+$ scores, and very few of these are among the SL2-enriched genes (Fig. 1b). We conclude that the microarray probing successfully identified genes that are *trans*-spliced to SL2.

Having performed a global search for genes that produce SL2 mRNAs, we determined whether their genomic structure indicated that they are located within operons. Each gene was evaluated as to whether it was likely to be downstream in an operon by the criteria described in Fig. 1 legend, using either the WormBase[5] or the