Massing life

Research into biomass and food chains attracts increasing attention, given the biosphere's capacity to sequester CO₂ from the atmosphere

Philip Hunter

Research into biomass—the mass of living organisms in a given area or ecosystem—has grown steadily during the past decade. This interest has been driven mainly by the need to assess, predict and mitigate the ongoing impact of human activities on ecosystems at different scales, particularly in light of anthropogenic climate change. Scientists, and to some extent policy-makers, are increasingly interested in how organisms and whole ecosystems react to environmental changes, and in whether the biosphere can sequester some of the carbon dioxide that is the main cause of climate disruption. In addition, biomass research has gathered momentum in its own right by shedding light on the long-range interactions in marine and terrestrial food chains that underpin the global carbon cycle.

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There have been plenty of surprises, such as the recent discovery of biomass hotspots in the so-called benthic zones at the bottom of oceans, where life had been thought to be relatively sparse. Deep ocean research has also shown that viruses are crucial for the benthic ecosystem and are responsible for the turnover of the organic matter on which bacteria—and ultimately all life at depths below 1,000 m—depends (de Leo *et al.*, 2010).

The study found that viruses killed more bacteria as depths increased and that they are responsible for 80% of deaths at the very bottom. The result of this viral carnage is the release of 0.37–0.63 gigatons (Gt; 10¹⁵ g) of carbon per year—a crucial source of nutrients for bacteria in particular and deep-sea ecosystems as a whole. The authors of the paper argue that this process actually sustains a large prokaryotic biomass and

allows the whole ecosystem to cope with the otherwise severe depletion of organic resources at great depths.

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Given this efficiency, bacteriophages must also be more abundant at great depths than thought previously—a fact now confirmed by several studies. Parada *et al.* (2007), for instance, found that although there was a tenfold decline for picoplankton, including bacteria, at a depth of 4,000 m—roughly the average depth of the ocean floor—viral concentrations suffered only a twofold reduction. It therefore seems that viruses themselves make a solid contribution to global biomass, although some researchers dismiss this as irrelevant as viruses are not independent living organisms. “Because viruses are not cellular, it is my opinion that they are part of the organisms they infect,” said William Whitman, head of the department of microbiology at the University of Georgia (Athens, GA, USA).

Yet, William Wiebe, also from the University of Georgia, suggested that viruses must make a big contribution, especially in the oceans, because they exist at such a high density throughout a huge volume of water. In fact, a recent study estimated that phage viruses beneath the sea ice in the Arctic Ocean were around 26 times more numerous than the bacteria they infected, and weighed about 0.02–0.05 g per m³, compared with the 0.27–0.85 g of their hosts (Steward *et al.*, 2007).

Discounting viruses, however, the two main components of biomass in terms of bulk are plants and prokaryotes (Fig 1). Until a decade ago it was thought that plants

make the largest contribution, particularly given the huge biomass locked up in trees, but prokaryotes might account for an equal amount. Whitman and Wiebe were two of the three authors of the first paper that made a serious attempt to weigh the world's prokaryotes (Whitman *et al.*, 1998). They assumed that the preponderance of the world's prokaryotes resided in three habitats—seawater, soil, and the sediment below the surface of both land and sea—and sampled areas considered to be representative of each. By extrapolation they considered the total weight of cellular carbon in prokaryotes was 350–550 Gt, and that this represented 60–100% of the total carbon bound in plants at any one time.

Carbon, of course, is not the only component, and biomass can be measured in different ways, sometimes within individual ecosystems; for example, fish farms could be taken as the complete total mass of all organisms in the water, but more commonly as the total dry weight after discounting water. Biomass can also be presented as a portfolio of different measurements, as some are most relevant in particular circumstances. Nitrogen content, for example, is a particularly important component of biomass in soil because its presence is essential for many plants, which lack the capability of sequestering it from the atmosphere and therefore rely on soil bacteria to fix it for them. Indeed, the contribution of prokaryotes dominates because they have a higher concentration of protein—and therefore nitrogen—than plants. The same holds true for phosphorus, which is an important constituent of nucleic acids. These are highly concentrated in bacteria, or indeed in any given cell, but plants have large intracellular spaces low in phosphorus and therefore contribute less to this measure. Whitman *et al.* estimated that the earth's prokaryotes accounted for 85–130 Gt of nitrogen and 9–14 Gt of phosphorus; in each case, about 10 times as much as plants.

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It would seem intuitive that primary producers account for the most biomass as each ‘trophic’ level relies on the one below for its carbon and other organic molecules. But this assumption ignores

the role of reproduction, the rate of which has an impact on the relative mass of different trophic levels; indeed, in some aquatic and marine systems, primary producers do not account for most biomass. The calculation also takes into account the relative sizes of the primary producers and the animals that consume them. On land, herbivores tend to be smaller or comparable in size to the plants they feed on; moreover, plants metabolize and reproduce relatively slowly. In the oceans and some freshwater ecosystems, primary producers are tiny phytoplankton with high rates of metabolism and reproduction. If their total biomass were larger than the primary consumers, such as krill, shrimps and forage fish, their population would explode. The dynamics of the ecosystem have therefore led to an expansion of consumers and a decline in the number of producers to reach equilibrium. This leads to the seemingly counter-intuitive inverted pyramid, where the mass of consumers is greater than that of producers.

Intuition has also been proven wrong in the case of insects, which collectively are the most successful animals both in terms of biomass and diversity. In the insect class, beetles constitute the biggest and arguably most successful order, with more than 350,000 known species—including the largest and smallest insects—colonizing almost all habitats. But in terms of biomass, they are dwarfed by ‘social’ insects—notably termites, bees, wasps and ants. Social insects have evolved the ability to live in colonies with much greater population densities than beetles, often comprising many clones of genetically identical individuals. As Edward O. Wilson, a US entomologist and conservationist, pointed out, social insects account for just 2% of all insect species, but more than half the total insect biomass (Wilson, 1990).

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The evolution of sociality does not lead automatically to an increase in biomass, even if it does enhance the prospect of

survival for a species through cooperation and pooling of resources. For biomass to increase, social insects need to husband resources more efficiently. Among social insects this has been accomplished through the creation of communities, which cooperate to gather food effectively from a wide area, whether this is nectar from plants or detritus from both plants and animals.

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In terms of generating biomass, sociality and community was the most successful evolutionary strategy until humans came up with an even more effective method around 10,000 years ago: agriculture. At that time the human population started to increase from its previously stable level of around 1 million to between 170 million and 400 million 2,000 years ago. The next significant growth spurt came with the industrial revolution in Europe where the population doubled in both the eighteenth and nineteenth centuries. Finally, modern medicine has enabled today's population of almost 7 billion, equating to a biomass of 100 million tonnes—far greater than other mammals, with the exception of domesticated animals, the numbers of which have increased in step with humans. Indeed, cattle continue to outweigh us in biomass, with 1.3 billion individuals scaling about 130 million tonnes and contributing to atmospheric greenhouse gas concentration by producing methane.

Biomass calculations are also shedding light on another man-made impact on the environment, namely the acidification of the oceans in response to rising levels of carbon dioxide in the atmosphere. It recently became clear that fish have an important role alongside marine plankton in sequestering carbon by absorbing calcium and then re-emitting it in their faeces as various forms of carbonate. However, their contribution was not clear as the total biomass of fish was previously unknown. Now, however, two independent studies have calculated fish biomass and have produced results in the same range by using entirely different methods to overcome the difficulty of directly measuring fish populations.

The first study, led by Simon Jennings from the Centre for Environment, Fisheries and Aquaculture Science in Lowestoft, UK, estimated total fish biomass at 0.9 billion tonnes (Jennings *et al*, 2008). The authors combined remote sensing temperature data with existing data on the underlying primary production of biomass, mostly through photosynthesis by phytoplankton. The second study, led by Rod Wilson from Exeter University in the UK, came to an estimate of two billion tonnes, based on the evaluation of fish catches, thus focusing on outputs rather than inputs of the system (Wilson *et al*, 2009). “Given the errors and uncertainty inherent in both methods it is impossible to say which is likely to be more accurate, but the encouraging thing is that such different approaches can yield similar results,” Jennings commented.

The second study computed biomass as a first step towards assessing the role of fish in the global carbon cycle through their production of calcium carbonate. Before this, marine plankton had been thought to account for nearly all oceanic carbonate production, but according to Wilson, fish produce 3–15% as much and possibly up to 45%, depending on various assumptions.

The study also indicated that, as the ocean becomes more acidic owing to anthropogenic carbon dioxide emissions, the rate of carbonate production by fish will increase. This finding led to a widely reported misconception when the study was published that fish could offset ocean acidification, when in fact the opposite could well be the case, according to Wilson.

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As he pointed out, the immediate effect of producing calcium carbonate, whether by fish or plankton, is an increase rather than decrease of ocean acidity, because alkaline calcium ions are removed from the water. The ultimate impact on oceanic pH thus depends on whether that carbonate redissolves so that the calcium ions are given back, or whether it sinks

Fig 1 | The different sources of biomass.

to the bottom, in which case the calcium ions are in effect taken out of circulation. In the latter case, the effect on fish or plankton metabolism would be a net increase in ocean acidity. "So yes, the question becomes what is the fate of that carbonate," Wilson said.

On this point Wilson has recently made progress with the finding that the carbonate produced by fish has a high magnesium content, which makes it more soluble. This means it could be that the fish carbonate dissolves in shallower waters than does some of the carbonate produced by plankton, thus keeping acidity down at lesser depths—at higher temperatures and lower pressures the capacity of the water to dissolve calcium salts is lower. However, the overall implications are rather ambiguous as they suggest that because fish probably tend to increase ocean acidity, overfishing could be said to be a good thing. But, as Wilson rightly pointed out, doing so would have a disastrous impact on the whole marine ecosystem.

Biomass research has also focused on the effects of human activities on whole land-based ecosystems and food chains. These systems are governed essentially by Liebig's law of the minimum, which states that the one fundamental resource or nutrient that is in shortest supply in a given place determines the rate of production. This resource could be oxygen, carbon dioxide, nitrogen, water, temperature, light, or even some of the minor nutrients.

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A major human effort in agriculture has been to increase the nitrogen content of soil by adding fertilizers, whether organic or inorganic. This boosts crop growth, but the

full impact on other organisms in the soil was poorly understood until a 2006 study led by Pete Manning at Imperial College in London, UK confirmed that soil nitrogen enrichment led to a biomass increase rippling out from plants across the whole ecosystem (Manning *et al*, 2006). "Higher plant biomass led to greater plant litter input to the soil, leading in turn to more fungal and bacterial biomass and a higher abundance of *Collembola* [springtails], which are primitive insects that feed on the fungal material," Manning said. "Similar findings have now been seen in field experiments where a greater diversity of plant species has produced a higher plant biomass, and this has translated to increases in the biomass of both microbes and soil animals."

Other ecosystems have different limiting factors constraining biomass increase in line with Liebig's law. In forests, for example, it has been shown that the rate of growth has already increased with elevated carbon dioxide levels. Evidence from field-grown trees suggests that a 300 parts

per million (ppm) increase in atmospheric carbon dioxide levels boosts the rate of photosynthesis in trees by 60% (Norby *et al*, 1999). If correct, trees should be photosynthesizing about 12% faster than two centuries ago, given the 70ppm increase in atmospheric carbon dioxide since the industrial revolution.

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The accumulating results from biomass research are helping scientists to understand the complex web of interactions in the global carbon cycle and the underlying food chains, and to identify the impact of human activities. But much more needs to be done to integrate the amassing knowledge into a more detailed picture of how carbon

and other elements flow in individual ecosystems and then on to the whole biosphere. In the light of ongoing anthropogenic climate change and the ever increasing concentration of greenhouse gases in the atmosphere, more biomass research is also important to direct policies that aim to mitigate the damage to ecosystems and biodiversity.

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