Agrochemicals, microbes and the environment

Sir: what is that stuff being sprayed on our sports field?

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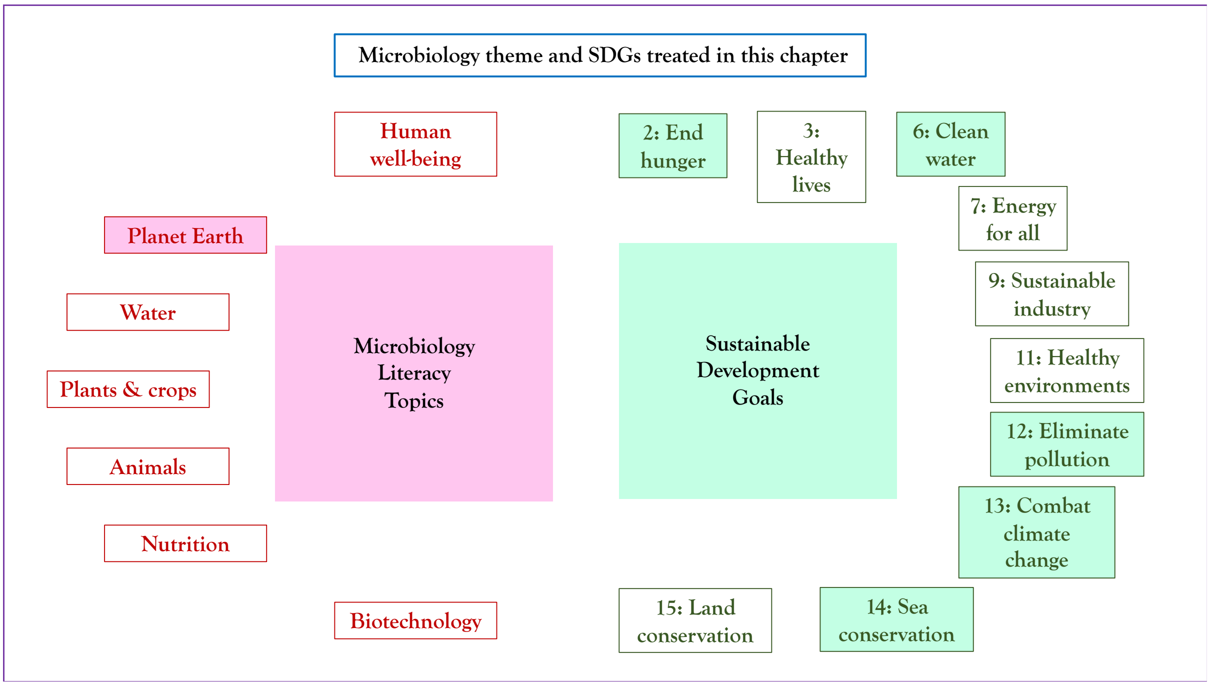
Agrochemicals

Storyline

Humans have massively altered the world's surface. We have converted over a third of the world's ice-free land area to farmland to grow food, and 1 % of the planet is built over. Within our urban settings we have converted wild places to sports fields, parks and gardens. All these areas are carefully managed by humans to ensure that the specific plants we want are able to grow in preference to others, and that these plants are healthy. To do this we use a range of agrochemicals including fertilisers and pesticides. Use of these chemicals comes at a high environmental cost. Production, transport and use of these chemicals results in greenhouse gas emissions. Once applied to soil, fertilisers can be converted by soil microbes to potent greenhouse gases. Soil microbes can develop capabilities to degrade pesticides, preventing their widescale accumulation and contamination of the environment. However both pesticides and fertilisers can migrate from soil and contaminate rivers, lakes, the oceans and our drinking water. In the future, microbes may be used as sustainable, environmentally friendly approaches to control plant health. Agrochemical use affects many sustainable development goals.

The Microbiology and Societal Context

The microbiology: microbial greenhouse gas formation; microbial adaptation; microbial biodegradation of chemicals; eutrophication and cyanobacterial blooms; microbial biocontrol agents; microbial biofertilisers; *Sustainability:* food supply; clean water; environmental pollution; global warming; sea conservation.



Agrochemicals: the Microbiology

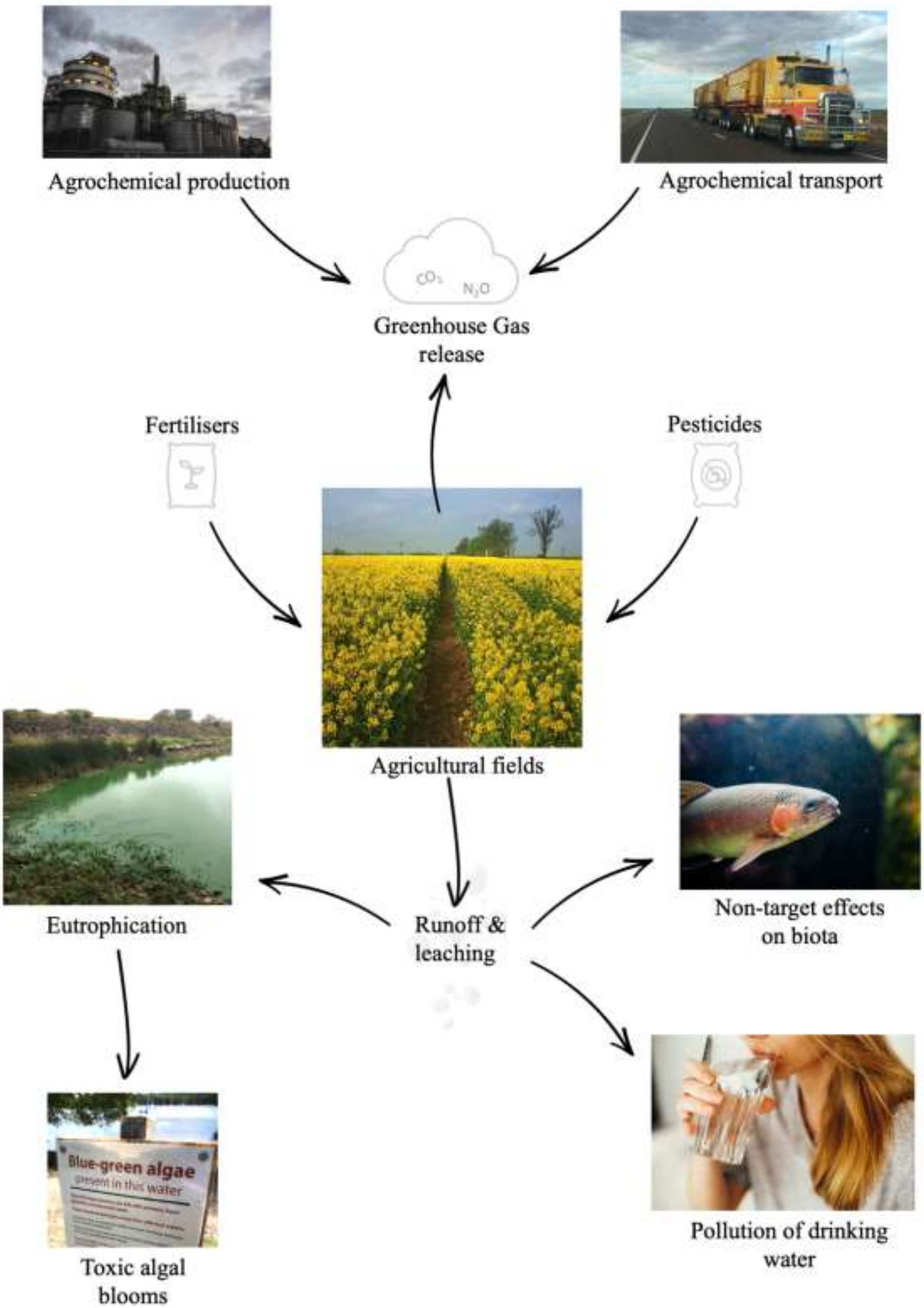
1. ***Plants managed in sports fields, gardens and as crops are given agrochemicals to keep them healthy.*** When we grow plants in soil, their growth rate is limited by the amount of nutrients, particularly nitrogen and phosphorus, which are available to the plant for uptake from the soil. For this reason, farmers spray fertilisers onto the soil to maximise their crop yields and farm profit, and groundskeepers apply fertiliser to boost grass density, strength and appearance. To make synthetic nitrogen fertiliser, N_2 gas from the atmosphere is fixed into ammonia, an industrial process which uses 1-2 % of the world's energy supply, representing a major contribution to the formation of greenhouse gases (GHG). However, without use of nitrogen fertiliser we would only be able to grow enough food for half of the world's population. Phosphorus fertilisers are manufactured from phosphorite rocks, a finite resource which may run out in the next century. Plant growth can also be reduced by weeds, insect pests and diseases caused by microbial pathogens. Farmers and groundskeepers apply pesticides to their plants to reduce the losses in yield, and the visual appearance of produce, that are caused by these pressures.

2. ***Agrochemicals applied to soil contribute to greenhouse gas emissions.*** Plants can directly take up mineral forms of nutrients, including ammonium (NH_4^+), nitrate (NO_3^-) and phosphate PO_4^{3-}) ions, which are contained in synthetic fertilisers. However, the nitrogen and phosphorus contained in soil organic matter, and organic fertilisers, such as urea, manures and slurries, is in organic form. Microbes in the soil break down the organic matter in these materials to mineral forms which can be taken up by plants, a process called mineralisation. During the mineralisation of nitrogen, organic nitrogen such as protein is first converted to NH_4^+, which is then transformed to NO_3^- by archaea and bacteria. During this process the gas nitrous oxide (N_2O) is released as a by-product. Further N_2O is produced by denitrification, which occurs when microbes in the soil use NO_3^- as a terminal electron acceptor under conditions of low oxygen availability, such as when the soil is waterlogged. N_2O is a potent GHG that has a global warming potential 298 times that of carbon dioxide. Further GHG are emitted when fossil fuels are burned in vehicles used for the transport and application of agrochemicals to cropping systems.

3. ***Pesticide persistence can damage ecosystems.*** Synthetic pesticides were first developed in the early 20th century. One of the most widely used early pesticides was the insecticide dichlorodiphenyltrichloroethane (DDT), which was used as an agricultural insecticide and also to contain the spread of diseases transmitted by insects, such as malaria and typhus. During the 1950s it was realised that pesticides like DDT persist in the environment, and can bioaccumulate in food chains, with predatory birds in particular accumulating DDT from the prey they ate. DDT was found to cause thinning of eggs shells, resulting in premature hatching of chicks and population decline in various species, including the bald eagle and peregrine falcon. Concerns about these effects were raised by Rachel Carson in her book 'Silent Spring', resulting in the birth of the environmental movement and regulations to reduce the environmental persistence and toxicity of pesticides.

4. ***Microbial communities adapt to degrade pesticides.*** Most modern pesticides are susceptible to biodegradation by bacteria and fungi in the soil, which use the chemical as a carbon and energy source. Microbial degradation therefore determines the persistence and fate of pesticides and their potential to damage ecosystems. Susceptibility of different pesticides to biodegradation varies because of differences in their chemical structure, and biodegradation rates

are also affected by soil organic matter and soil clay content, which pesticides can stick to, affecting their bioavailability to degrader organisms. Biodegradation rates are also influenced by temperature, water content and availability of nutrients such as nitrogen, which can affect the growth of degrader organisms.



Environmental impacts resulting from the use of agrochemicals

Microbes can rapidly develop metabolic capabilities to degrade novel chemicals such as pesticides. This is a result of fast reproduction rates, which can result in the selection of mutations in enzymes and metabolic pathways which are conducive for biodegradation, and also horizontal gene transfer, in which bacteria take up DNA from their environment, which can result in spread, and selection, of biodegradation pathways within microbial populations. These processes of 'adaptation' mean that when a new chemical is released into the environment, although it may initially be persistent, novel biodegradation pathways can emerge and chemical biodegradation rates in the environment can increase over time. While this is generally beneficial, some pesticides rely on short term persistence in the soil to exert control of their target pest, and the development of such 'enhanced' microbial degradation may result in the loss in pesticide effectiveness.

5. ***Agrochemical use can pollute drinking water.*** NO_3^- and many pesticides are highly soluble in water, so that when water from rainfall percolates into soil, they move vertically down the soil profile, a process termed leaching. This can carry NO_3^- and pesticides to groundwater and aquifers. Furthermore, when rain falls on to fields it may carry soil and soluble materials horizontally, transferring them to surface freshwater bodies such as streams, rivers and lakes, a process known as run-off. Microbial populations in aquifers are very low, so that once a pesticide reaches an aquifer, biodegradation is slow, and the pesticide can be highly persistent. As a result, pesticide pollutants can still be detected in aquifers long after they have been banned from use. Sometimes microbial biodegradation of pesticides can result in the formation of metabolites which have different properties to the parent compound. For example, the herbicide dichlobenil is degraded by soil microbes to 2,6 dichlorobenzamide (BAM), which is slowly degraded by soil microbes, and also highly mobile, and therefore susceptible to leaching through soil. This has resulted in BAM being a widely encountered contaminant of groundwater. Since we use aquifers and water from rivers and lakes for our drinking water, contaminants pose a risk to human health. Before it can be used for human consumption, water is treated to remove contaminants, which comes at a high financial cost and uses energy, further contributing to GHG emissions. Aquifers which are highly contaminated with pesticides can be cleaned using bioremediation. This involves the addition of pesticide degrading microbes, or the pumping of oxygen or nutrients into the aquifer to remove constraints to microbial activity and stimulate microbial biodegradation processes.

6. ***Fertilisers cause eutrophication resulting from growth of cyanobacteria in water bodies.*** In aquatic habitats, growth of organisms which use sunlight for energy (phototrophs) is limited by availability of nitrogen and phosphorus when light is plentiful. When NO_3^- and PO_4^{3-} reach freshwater and marine water bodies following leaching or run-off, it can result in rapid 'blooms' in the populations of algae that live in the water, particularly dinoflagellates and cyanobacteria. Cyanobacteria are photosynthetic bacteria and can release diverse toxins into the water (e.g. microcystin). These pose a risk of poisoning to humans using the water for leisure activities, and animals which swim in or drink the water. Algal blooms also deplete inorganic carbon which is required for shell formation by molluscs, and limit light penetration, affecting growth of water plants. High rates of photosynthesis by algae can result in elevated pH during the day, impairing the health of fish and invertebrates which use chemical cues for survival, such as to detect prey and predators. When the blooms die, they are decomposed by aerobic microbes, a process that depletes oxygen in the water, resulting in the development of anoxic zones, which causes the death of aquatic animals. While some ocean regions experience natural cycles of anoxia, the number of such dead zones in the world's oceans is rising rapidly, increasing from

10 in the 1960s to over 400 today, because of eutrophication. The Gulf of Mexico dead zone first appeared in the 1970s and now occurs annually between May and September, covering between 5000 and 22 000 km^2.

Agrochemicals: definitions and uses

Fertilisers	Pesticides
Fertilisers are concentrated sources of plant nutrients which are used to correct deficiencies and improve growth and yield of agricultural crops and the appearance of gardens, parks and sports fields. Nutrient deficiencies cause symptoms such as yellowed or reddened leaves, and poor growth, flowering and fruiting. Synthetic fertilisers are inorganic products manufactured through industrial processes. They can come in the form of pellets, granules, powders or liquids. Organic materials are also used as fertilisers. These may be synthesised, such as urea, or derived from animals and plants, such as manures, compost and seaweed. The nutrients in these materials are in organic forms, which must be mineralised by soil microbes to inorganic mineral forms before they can be used by plants. Nitrification inhibitors are compounds which slow microbial nitrification processes, allowing greater synchrony of NO_3^- availability with crop demands, thereby reducing the potential for leaching and denitrification. Solid waste from wastewater treatment plants is sometimes used as a fertiliser, although these materials may contain daily use chemicals such as antibiotics, and heavy metals, which may contaminate soil and impact soil biota.	Pesticides are defined as any material used to kills pests. They can be used in parks, playgrounds, playing fields, golf courses, gardens and on transport infrastructure such as railway lines. Pesticides used in agriculture are often called crop protection products, as they prevent pests from causing economic damage to crops. A typical UK wheat crop will be sprayed with pesticides 6 times, using 16 different substances to control insects, nematodes, fungi, molluscs and weeds. Pesticide residues can be found in food and beverages. While these are very rarely in high enough concentrations to cause harm, many pesticides have the potential to act as endocrine disruptors and there is concern about the potential for long term exposure to pesticides to affect human health. As a result of concerns about pesticide effects on human health and the environment, many pesticides have been banned or their use restricted. This can result in damaging crop losses to farmers. Biopesticides, in which pest control is brought about by microbes, pheromones, insects and plant extracts are beginning to replace the synthetic chemicals which have traditionally been used as pesticides.

7. **Microbes are a sustainable alternative to synthetic agrochemicals.** The environmental consequences of our reliance on agrochemical use to grow food has led to a search for more sustainable options. A wide range of commercial products are now available which use microbes as biological control agents (BCA) of insect pests and microbial pathogens. These rely on using natural antagonists which may inhibit their target through parasitism or the production of inhibitory metabolites. One of the first commercial biological control agents, developed in the

1950s, was the soil bacterium *Bacillus thuringiensis*, which makes a protein which is toxic to insect larvae. This bacterium is an effective control agent of diverse crop pests such as moths and beetles. Numerous other microbial biocontrol agents of insects, nematodes and microbial pathogens have been discovered and numbers of BCA on the market is increasing yearly. Options are also being developed to replace fertilisers with microbial 'biofertilisers' which enhance nutrient availability to crops. This includes root-inhabiting symbiotic mycorrhizal fungi that mobilise and assimilate nutrients from the soil, which are then traded with their plant partner in exchange for sugars and lipids. Crop plants have also been successfully transformed with specific microbial genes to confer resistance to pests and pathogens and enhance nutrient uptake. Of particular current interest are bacteria which inhabit nodules within the roots of leguminous plants such as peas and beans. These bacteria carry nitrogenase (nif) genes which fix N_2 from the atmosphere into ammonia, which is transferred to the plant in exchange for sugars. Leguminous crops do not therefore require nitrogen fertilisers There is interest in transforming cereals with bacterial nif genes, to enable cereal crops to fix their own nitrogen. This would bring about a immense reduction in global fertiliser demand.

Relevance for Sustainable Development Goals and Grand Challenges

Microbial aspects of agrochemical use relate to a range of SDGs (microbial aspects in italics), including

- **Goal 2: End hunger, achieve food security and improved nutrition and promote sustainable agriculture** *(end hunger and malnutrition, increase agricultural productivity).* Use of fertilisers and pesticides is important in providing us with food to eat. However, making, transporting and using these products contributes to global warming. Sustainability can be improved by devising methods for producing food which use biological approaches for crop nutrition and control of pests and diseases.

- **Goal 6: Ensure availability and sustainable management of water and sanitation for all** *(assure safe drinking water, improve water quality, reduce pollution, protect water-related ecosystems).* Fertiliser and pesticide use results in contamination of drinking water, and fertilisers promote algal blooms which can be toxic to humans and wildlife and result in eutrophication.

- **Goal 12: Ensure sustainable consumption and production patterns** *(achieve sustainable production and use/consumption practices, reduce waste production/pollutant release into the environment, attain zero waste lifecycles, inform people about sustainable development practices).* Current use of fertilisers and pesticides to grow food and manage urban spaces results in losses to the environment. In particular phosphorus is a non-renewable resource and sources may run out in the next century. Approaches need to be developed for closed loop nutrient cycles, in which nutrients are retained and recycled in the soil, preventing losses, and biological approaches for plant nutrition to reduce the need for fertiliser use.

- **Goal 13: Take urgent action to combat climate change and its impacts** *(reduce greenhouse gas emissions, mitigate consequences of global warming, develop early warning systems for global warming consequences, improve education about greenhouse gas production and global warming)*. Nitrogen fertiliser application to soil is associated with microbial production of nitrous oxide, a major climate gas.

- **Goal 14: Conserve and sustainably use the oceans, seas and marine resources for sustainable development** *(reduce pollution of marine systems by toxic chemicals/agricultural nutrients/wastes like plastics, develop mitigation measures for acidification, enhance sustainable use of oceans and their resources).* Fertiliser use results in eutrophication and the development of dead zones in the oceans.

Potential Implications for Decisions

1. ***Individual***
    a. Weighing up microbial and non-microbial factors to consider how personal actions can make a difference
    b. Personal choice of agrochemical use in the garden or as a farmer
    c. Acceptance of reduced crop yield, vegetables with imperfections, less aesthetic greenspace
    d. Choice of food products, purchase of food produced in systems with less intensive agrochemical use e.g. organic

2. ***Community policies***
    a. Management of urban greenspaces; choice of inputs to parkland and sports fields and acceptability of lower visual appeal when inputs are lowered
    b. Eutrophication of local lakes and rivers; loss of amenity value, health impacts during water-based leisure activities, toxicity to pets and wildlife
    c. Contamination and closure of local lakes and drinking water wells

3. ***National policies relating to agrochemical use***
    a. Environmental quality targets while maintaining food security
    b. Drinking water quality standards
    c. Greenhouse gas production and global warming
    d. Eutrophication and impacts on fisheries and tourism

Pupil participation

1. ***Class discussion of the issues associated with agrochemical use***

2. ***Pupil Stakeholder Awareness***
    a. Agrochemical use has positive and negative consequences for SDGs. Which of these are most important to you personally and as a class?
    b. Is it OK to pollute the environment if it ends global malnourishment?
    c. Consequences of food choices - what swaps could be made to reduce environmental impact?
    d. How could you use this information to make more sustainable choices at home i.e. gardens, vegetable patches, allotments?
    e. Would you eat genetically modified crops containing microbial genes, if it allowed the crops to be grown with a far lower environmental footprint than non-genetically modified crops?

f. How do you think the efficacy and reliability of biological control-based approaches to provide plants with fertiliser and reduce pests would compare with use of synthetic chemicals?

The Evidence Base, Further Reading and Teaching Aids

Royal Horticultural Society: Fertilisers and how they are used
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European Nitrogen Assessment
https://www.youtube.com/watch?v=uuwN6qxM7BU
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Glossary

Aerobic microbes: require the presence of free oxygen to grow
Anoxic: depleted in oxygen
Aquifer: an underground body of porous rock or sediment which is saturated with groundwater. Wells can be drilled into aquifers to collect water for drinking and irrigation
Bioavailability: the amount of a chemical which is in a form which can be taken up by, or exert a response from, an organism
Biodegradation: the breakdown of an organic chemical by microorganisms
Bloom: a rapid increase in the population of algae in a water body. This can result in green, yellow or red coloured water.
Dichlobenil: an organochlorine herbicide used against perennial weeds in crop and other uses. Banned by the EU since 2009 but currently approved for use in the USA and Australia
Dinoflagellate: single celled eukaryotic algae which inhabit marine and freshwater systems

Endocrine disruptor: chemicals which interfere with the hormonal messenger system within animals which regulates bodily functions such as growth and reproduction. This may result in cancers, birth defects and growth disruption
Genetic modification: changing the genetic make up of an organisms by adding genes from a different organism, such as by the transfer of a microbial gene into a plant
Greenhouse gas: gases in the atmosphere which prevent heat that the sunlight brings from escaping back into space, which results in global warming
Groundwater: water that exists below the soil surface
Pheromone: chemicals that are secreted by animals which affect the behaviour of another individual of the same species. In crop systems these can be used to lure pests into traps or to prevent mating
Terminal electron acceptor: the last compound to receive an electron in an electron transfer chain. Under aerobic respiration, oxygen is used as the terminal electron acceptor, while under anaerobic (low oxygen) conditions oxygen is replaced by other materials, including NO_3^-, Fe_3^+ and SO_4^-