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Urbanization, Agriculture, and Carbon: Balancing Ecosystems for the Future

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Abstract According to the United Nations, the global population is 8 billion in 2024 and is projected to reach 9.8 billion by 2050, with 68% of people living in urban areas, up from 56% in 2020. This rapid urbanization means fewer individuals will be directly involved in food production, making efficient, large-scale agricultural systems essential for feeding the growing population. Advanced technology and strategic land use will be crucial in meeting this demand. A balance between humans, plants, and animals is key to sustaining the environment and fulfilling global nutritional needs. In this interconnected system, plants capture carbon dioxide, produce food, and release oxygen, forming the foundation of the Earth's ecosystem. While humans and animals rely on plants for nourishment, animals and microorganisms convert plant materials that humans cannot consume (like grass) into nutrient-dense food. Additionally, livestock manure enriches soil fertility, supporting crop growth in a continuous, beneficial cycle. This interdependence creates a biological system in which plants, animals, and humans benefit one another, emphasizing the importance of a balanced approach to agriculture.

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Plants: the base of the ecological pyramid.

Plants are the basis of the food chain and the energy pyramid in Earth's ecosystems. Through photosynthesis, they convert solar energy into chemical energy stored in their biomass. This energy is then passed on to herbivores (primary consumers) and subsequently to carnivores (secondary and tertiary consumers). Without plants at the base, the rest of the pyramid would collapse, as they are the primary source of food and energy for nearly all life forms on Earth.

Plants can be categorized into three main groups based on their photosynthetic processes: C3, C4, and CAM plants.

C3 plants, including wheat, rice, and most vegetables, use a standard photosynthetic method where carbon dioxide is fixed into a three-carbon compound. They thrive in cool, moist environments but are less efficient in high temperatures and intense sunlight. These plants are crucial to the human diet and to wild herbivores that rely on grasslands. Trees also belong to this group, contributing significantly to both natural ecosystems and agriculture.

C4 plants, such as corn, sugarcane, and sorghum, have an advanced photosynthetic pathway that captures carbon dioxide more efficiently, even in hot and dry conditions. This adaptation allows them to grow rapidly and produce high biomass, making them extremely valuable in agriculture. C4 plants are essential in human diets, particularly in hot regions of the world; for example, sorghum is a staple in Africa, while corn originated in South America and has since spread globally.

CAM plants (Crassulacean Acid Metabolism), including cacti, agave, and pineapple, are adapted to arid environments. They open their stomata at night to capture carbon dioxide, reducing water loss and storing it for use during the day. This unique process enables these plants to survive in extreme climates where water is scarce.

Together, these three groups of plants play diverse roles in ecosystems and agriculture. Of the three, C4 plants (like corn, sugarcane, and sorghum) are the most efficient at photosynthesis, capturing and using sunlight and carbon dioxide much more effectively, especially in hot, sunny climates. This efficiency allows them to grow faster and produce more biomass. Plants for the C3 group (such as wheat, rice, and most vegetables) rank second in efficiency; they are less effective at capturing carbon dioxide, particularly under intense sunlight and high temperatures, and are more common in cooler, wetter environments. On the other hand, CAM plants, while excellent at conserving water, capture less carbon per unit area compared to C3 and C4 plants. However, they play a critical role in carbon sequestration in arid environments where other plants cannot thrive. Additionally, desert soils can store carbon through microbial activity and root biomass, making these ecosystems more important in the carbon cycle than they might initially appear. If we were to rate these three groups of plants as carbon sinks of Earth's environment, with C4 plants set at 100%, C3's would rate at 60-70%, and CAM's at 20-30%.

Animals: Nature's Energy Converters and Nutrient Cyclers

Animals play a vital role in ecosystems as energy converters and nutrient cyclers. They consume plants, both directly and indirectly, converting the energy stored in plant biomass into nutrient-dense forms such as meat, milk, and eggs. In this process, they provide essential proteins, fats, and other nutrients that are critical for the survival of many organisms, including humans. Additionally, through their waste products and other activities, animals contribute significantly to nutrient cycling, enriching the soil and promoting plant growth.

Herbivores primarily consume C3 and C4 plants, making them key players in converting solar energy into forms that support higher levels of the food chain. Grazing animals like cattle, sheep, and goats feed on grasses, many of which are C3 plants in the wild. In developed countries, these animals often consume C4 plants such as corn and sorghum, while in tropical, less developed cattle production systems, sugarcane is a common feed source. C4 plants thrive in hot, sunny environments, producing large quantities of forage that herbivores can convert into nutrient-rich products. In cooler, more temperate climates, herbivores rely more on C3 plants, such as grasses for grazing, and wheat and barley biomass in less developed regions. Although C3 plants are less efficient at carbon capture compared to C4 plants, they provide a consistent food source across the different seasons.

Animals also interact with CAM plants, particularly in arid environments. Herbivores adapted to desert ecosystems, such as camelids and certain species of goats, feed on CAM-type plants like cacti and agave. While CAM's are not as efficient in terms of energy production as C4 or C3 plants, they play a crucial role in providing feed in harsh, water-scarce environments. The consumption of CAM plants by these animals helps maintain ecological balance in desert ecosystems.

Beyond energy conversion, animals serve as nutrient cyclers within ecosystems. Through their digestion and excretion processes, they break down plant matter, returning essential nutrients to the soil. Livestock manure, for example, is rich in nitrogen, phosphorus, and organic matter, which are vital for plant growth. This recycling of nutrients not only enhances soil fertility but also promotes the growth of both C3 and C4 plants, creating a continuous cycle of energy production and consumption. This dynamic is particularly important in agricultural systems, where the integration of livestock and crop production can lead to more sustainable land use practices.

Humans: Ultimate Consumers and Ecosystem Modifiers

Humans have evolved significantly in their relationship with their environment, shifting from early vegetarians to hunters and, eventually, to agriculturists. Initially, our ancestors were largely herbivores, consuming a plant-based diet composed mainly of fruits, nuts, seeds, and leaves from C3 plants. This diet provided essential nutrients and energy in a time when humans were foragers, living off the land around them.

The transition to hunter-gatherer societies marked a significant shift in human diet and behavior. With the discovery of hunting tools and the control of fire, early humans began incorporating meat into their diets. This newfound status as omnivores allowed humans to adapt to a variety of environments, from forests to savannas and even deserts, where they also learned to consume CAM plants when food or water sources were scarce. As hunter-gatherers, humans moved with the seasons, impacting ecosystems but not significantly altering them.

The next major shift came with the advent of agriculture about 10,000 years ago. Humans transitioned from nomadic hunter-gatherers to settled agriculturalists, leading to the cultivation of both C3 plants (like wheat, rice, and barley) and C4 plants (such as corn and millet). This period marked the beginning of humans as ecosystem modifiers. By domesticating animals and cultivating land, humans began to reshape ecosystems to suit their dietary and economic needs. The development of agriculture allowed for larger, more stable human populations and paved (literally today!) the way for urban societies. The shift also led to the domestication of livestock, transforming the human diet and impacting natural nutrient cycles. Nowadays animals are fed both C3 and C4 plants, converting plant biomass into nutrient-dense foods like milk and meat, thus enhancing food security and diversity. This has allowed the transition from a more agriculturalist society to today's urban sprawl.

In the present day, humans continue to alter ecosystems through large-scale agriculture, urban development, and technological advancements. The demand for both plant and animal products has led to the expansion of agricultural lands, intensive livestock farming, and changes in land use. As we manage agricultural systems to maximize food production, we inadvertently alter natural ecosystems, affecting biodiversity, soil health, and the global carbon cycle. From their origins as vegetarians and hunter-gatherers to the architects of agrarian societies, humans have become the ultimate consumers and modifiers of the environment.

Plants, Animals, and Humans: Interconnected Roles

As of 2022, approximately 56% of the world's population lived in urban centers, according to data from the United Nations. This figure is projected to increase, with estimates suggesting that nearly 68% of the global population will live in urban areas by 2050 (United Nations, World Urbanization Prospects). The relationship between plants, animals, and humans has fundamentally changed, drastically altering the environment. The shift to urban life means fewer people are directly involved in food production, creating a heavy reliance on large-scale agricultural systems. However, urbanization has also driven innovations in sustainable agriculture, including urban vertical farming, hydroponics, and regenerative agriculture practices. These methods reduce land use, improve efficiency, and mitigate some of the environmental impacts of industrial-scale farming, demonstrating that urban areas can also contribute to sustainable food production. These systems must cater to massive populations and the resulting high demand for food, particularly for products like meat and dairy.

To meet this demand, agricultural practices have intensified, shifting heavily to C4 plants like corn, a big biomass producer. Cornfields nowadays occupy vast areas that were once natural grasslands and forests, changing the balance of the carbon cycle. However, and as we addressed before, C4 plants like corn are more efficient in capturing carbon dioxide than many C3 plants (pasture) found in native ecosystems, and they contribute to increased photosynthesis in some regions. However, their role in long-term carbon sequestration is limited because their biomass is quickly harvested and consumed, resulting in the rapid return of carbon to the atmosphere as CO_2 or methane. Unlike forests or perennial grasslands, which store carbon for extended periods, annual crops like corn have a shorter carbon cycle that does not contribute as significantly to long-term carbon storage. Livestock, especially high-yield animals, consumes large quantities of these C4 plants, converting them into nutrient-dense foods like meat and milk. However, while C4 plants efficiently capture CO_2, livestock digestion and manure decomposition release methane (CH_4), a greenhouse gas with a higher warming potential than CO_2 over a short-term horizon. The overall impact of livestock on the carbon cycle depends on balancing the carbon sequestration from their forage crops with methane and nitrous oxide emissions from manure and digestion. During this process, much of the carbon captured is re-released into the atmosphere as methane and carbon dioxide through animal digestion, manure decomposition, and land-use changes. As a result, while photosynthesis may have increased due to extensive corn cultivation, the net effect on the carbon cycle is more complex, with increased greenhouse gas emissions altering the environment.

The expansion of urban populations has also resulted in further environmental alterations, including habitat loss, deforestation, and the conversion of natural ecosystems into agricultural land. This shift disrupts biodiversity and soil health, creating a cycle where intensive farming becomes necessary to sustain food production, but at the expense of an ecological balance.

World distribution of the main three type of plants

Estimating the amount of carbon dioxide consumed by plants in various regions provides insight into the role of different ecosystems in global carbon sequestration. **Forests**, which cover approximately 4.94 billion hectares of the Earth's land area, are the most significant carbon sinks. According to the Intergovernmental Panel on Climate Change (IPCC), forests sequester an average of 4.9 to 17.3 metric tons of carbon dioxide per hectare per year. Using a mid-range value of 11.1 metric tons of carbon dioxide per hectare per year, forests collectively absorb globally around 54.9 billion metric tons of carbon dioxide each year, highlighting their key role in mitigating climate change. This immense capacity is why forests are often referred to as the "lungs of the planet." Just as lungs take in air and release carbon dioxide, forests absorb vast amounts of carbon dioxide and produce oxygen through photosynthesis. This natural cycle is essential for maintaining atmospheric balance, regulating climate, and supporting diverse ecosystems. Without forests fulfilling this role, carbon dioxide concentrations would rise dramatically, further worsening climate change.

Grasslands, covering about 4.13 billion hectares worldwide, also play a significant role in carbon sequestration. Research by Conant et al. (2001) estimated that grasslands sequester between 1.2 to 3.7 metric tons of carbon dioxide per hectare per year. Assuming an average rate of 2.5 metric tons of carbon dioxide per hectare per year, these ecosystems absorb roughly 10.2 billion metric tons of carbon dioxide annually, making them vital for carbon storage and ecological balance.

Croplands, which occupy approximately 1.9 billion hectares worldwide, have a lower but still significant carbon sequestration potential. The IPCC suggests that croplands sequester 0.5 to 2.5 metric tons of carbon dioxide per hectare per year, depending on crop type and farming practices. Assuming an average rate of 1.5 metric tons of carbon dioxide per hectare per year, croplands absorb around 2.82 billion metric tons of carbon dioxide annually. This highlights the importance of sustainable farming practices to enhance croplands' ability to capture carbon.

Arid regions, including deserts and semi-arid areas, cover about 5.26 billion hectares and have the lowest carbon sequestration rates due to their sparse vegetation. According to Lal (2004), these areas sequester only 0.05 to 0.25 metric tons of carbon dioxide per hectare per year. Using an average of 0.12 metric tons of carbon dioxide per hectare per year, the global carbon uptake for arid regions is estimated at around 0.65 billion metric tons annually

In total, these estimates suggest that the Earth's forests, grasslands, croplands, and arid regions collectively sequester approximately 68.6 billion metric tons of carbon dioxide each year.

Although these figures can vary depending on factors such as plant species, climate, soil health, and land management practices, they underscore the importance of each ecosystem in maintaining the global carbon cycle's balance.

Among these ecosystems, forested areas use up the most CO_2, accounting for most of the carbon sequestration. Their dense biomass and highly efficient photosynthesis process make forests unmatched in their ability to capture and store carbon. In comparison, grasslands absorb around 10.2 billion metric tons of carbon dioxide annually, croplands around 2.82 billion metric tons, and arid regions through their CAM plants the least, with an estimated uptake of 0.65 billion metric tons per year. This critical function of forests as carbon sinks further justifies their title as the "lungs of the planet," highlighting their essential role in stabilizing the climate and supporting life on Earth.

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What can we do in the future to increase carbon dioxide utilization?

By comparison, protecting existing forests and reforesting some grasslands would have the most significant impact on reducing carbon dioxide emissions. Forests are the most effective carbon sinks due to their dense biomass and efficient photosynthesis. Therefore, efforts to preserve current forests, combat deforestation, and expand forested areas through reforestation would provide the greatest potential for carbon sequestration.

Turning some grasslands into forested areas could also enhance carbon capture. Grasslands do play a role in carbon storage, but forests sequester more carbon dioxide per acre. However, this transition should be carefully managed since grasslands support unique ecosystems and biodiversity that forests do not. Additionally, some grasslands, especially in arid and semi-arid regions, are not naturally suited for forest growth.

In contrast, agricultural land practices, while important, have a more limited impact on carbon dioxide sequestration. Implementing sustainable farming practices like no-till agriculture, crop rotation, cover cropping, and using organic fertilizers can increase the carbon storage capacity of croplands and improve soil health. However, the carbon sequestration potential of croplands is much lower compared to forests. Therefore, while sustainable agriculture practices contribute to overall ecosystem health and help reduce other emissions (like methane and nitrous oxide), they play a supplementary role in mitigating carbon dioxide emissions compared to forest conservation and expansion.

In summary, the most impactful strategy to reduce carbon dioxide emissions involves protecting forests and reforesting where feasible. Agricultural land practices are still important for reducing emissions and maintaining soil carbon, but they have a less direct influence on carbon dioxide reduction than forest management. However, methane from livestock is a short-lived climate pollutant, meaning that if emissions remain stable or decrease, their warming impact is reduced more quickly than CO_2. Implementing methane-reduction strategies, such as improved manure management and dietary adjustments for livestock, can provide faster climate benefits compared to CO_2 reduction alone.

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