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Image courtesy of Tamaryin Godinho

How much carbon is locked in that tree?

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Biology, maths, and the SDGs: estimate the CO_2 absorbed by a tree in the schoolyard and compare it to the CO_2 emissions of a short-haul flight.

Introduction

Global warming and the associated climate change are the greatest challenges facing humankind over the next ten years. A reduction in the levels of the greenhouse gas carbon dioxide (CO_2) plays a key role in mitigating climate change. As trees absorb CO_2 to generate their own biomass, they are part of a global strategy to reduce CO_2 levels. But how many trees are needed to offset one flight, for example?

This project starts with the following question: how many trees from the schoolyard are needed to remove the CO_2 released when someone takes a plane trip? The worked example in this article is based on 680 kg of CO_2, which is one person's CO_2 emissions for a round-trip holiday from Germany to Mallorca by air, but teachers can also pick a destination of equivalent distance from their city or look up the emissions for a more locally relevant route.

In the following materials, students estimate the carbon-storage capacity of a tree in the schoolyard or nearby and compare that to the CO_2 emissions of an aeroplane trip, as well as using a Geogebra sheet to better understand intercept theorem. In addition to mathematical content, students recognize the importance of trees in mitigating anthropogenic CO_2 emissions through CO_2 uptake through photosynthesis and reflect on CO_2 emissions in everyday life. This multidisciplinary project ties together curriculum topics from multiple subjects, from maths (geometry and ratios) to biology (photosynthesis) and chemistry (organic compounds and molecular masses). It also ties in with the 17 UN sustainable development goals (SDGs), of which the preservation and protection of the environment on land and water, as well as access to quality education, are key objectives.

The activities are suitable for students aged 11–16, with younger students working through the steps and the teacher explaining everything, and more independent problem-solving and in-depth discussion for older students.

How much carbon do trees store?

Trees need CO_2 for their growth, but too much CO_2 is responsible for global warming. To slow down the resulting climate change and to limit global warming to 1.5°C, according to the Paris Climate Agreement of 1995, CO_2 emissions have to be reduced to net zero by 2050 and greenhouse gases have to be removed from the atmosphere by 2100.[1–3] Currently, forests are a widespread strategy to remove CO_2 on a broad scale.[3]

Students should know that trees absorb CO_2 and understand the role of CO_2 as a greenhouse gas in the atmosphere. However, it is often wrongly assumed that CO_2 is stored. Trees only use carbon (C) to generate biomass by photosynthesis. If one wants to describe the climate effect of trees correctly, one must speak of carbon binding and not of CO_2 binding.

To estimate the amount of CO_2 taken up by a tree, one has to estimate the volume of the tree based on its height and diameter at breast height (DBH), defined as 1.3 m, which is the internationally standardized height at which to determine a tree's diameter.[4,5] A common method for estimating the height of a tree is based on the so-called forester triangle (the walking-stick method), which is based on the intercept theorem. Subsequently, the weight of the calculated volume is determined with the help of the specific weight of the wood of the respective tree species. Notably, this does not include the roots and the amount of biomass, such as sugars given to fungus via the roots into soil, and in general, the roots contribute approximately 30% of the total biomass of a tree.[5–7] Moreover, the sugars from photosynthesis are also used for growth, respiration, and conversion into amino acids and lipids. Therefore, calculations in this activity reflect a rough estimation.

A forest in southern Germany
Image courtesy of Tamaryin Godinho

Given that approximately 50% of the dry weight of wood is carbon (although this is a simplification: C content varies among species[8]), one has to divide the calculated weight by two to obtain the amount of C in kg. Finally, to calculate the mass of CO_2 absorbed, the C content of the tree must be multiplied by 3.67 (see molecular mass of CO_2).

Considering, that every tree species has its own shape and weight, there are different estimation tables available. For simplicity, this activity does not differentiate between different tree species, but is limited to [deciduous broadleaf and coniferous trees].

Activity 1: Introduction to the problem

Before proceeding with the practical part of the lesson, a class discussion introduces students to the main question and encourages them to think about the different aspects of the answer. This activity should take around 30 mins.

Materials

- Tree carbon estimation tables, which give approximate estimates of the amounts of atmospheric carbon conifers and broadleaf trees of different sizes have incorporated into their above-ground biomass
- Optional: atlas and a pair of compasses or access to an online map tool with a radius calculator (e.g., this radius-around-a-point tool)

Procedure

1. Introduce the main question: one person causes 680 kg of CO_2 release during a round trip of 2686 km (1343 km each way) by air, which is the distance from Düsseldorf (Germany) to Mallorca and back.
   How many trees are needed to remove this 680 kg of CO_2 from the air?
2. Optional: encourage students to use the atlas and pair of compasses, or online maps with a radius calculator tool, to find a travel destination that is approximately 1343 km from their nearest airport.
3. Ask what information you'd need to estimate the amount of CO_2 fixed by a tree in its life so far. The first question is where does the CO_2 absorbed by plants go? You can mention photosynthesis as a hint.
4. Optional: depending on the ages of the students, you might discuss some of the compounds trees build from the products of photosynthesis, like cellulose and lignin, and look up their chemical structures and identify the positions where carbon is.
5. Having established that much of the carbon from CO_2 fixation ends up in the wood, the next question is how much wood mass does a particular tree contain? What parameters does this depend on? Students should be able to figure out that this depends on the volume, which will be influenced by the size, for example, height and girth, of the tree. Older students might also consider wood density.
6. Introduce the tree carbon estimation tables, and explain that they can be used to estimate that amount (mass) of wood in a tree with a particular height and diameter at breast height (DBH). Mention that this measures the above-ground mass only, and neglects other ways trees might add biomass to the soil, so it underestimates the total carbon fixation.

Activity 2: Measuring the height and diameter of a tree in the schoolyard

In this activity, students select a tree, measure its DBH, and use a forester's triangle to measure the height. The forester's triangle is first employed before teaching intercept theorem to show the practical relevance of this method.

This activity takes around 30 mins.

The forester's triangle

- The forester takes a stick and places one end of the stick on their shoulder with their arm outstretched. The stick is then exactly as long as their arm (hand-to-shoulder distance = hand-to-eye distance when using the triangle)
- Subsequently, they align the stick vertically so that an imaginary line between their eye and hand forms a right angle (figure 1)
  IMPORTANT: the forester holds their hand at eye level!
- The forester moves away from the tree until they can see the top of the tree above the tip of the stick.
- The height of the tree corresponds approximately to the distance between the forester and the tree plus the height of the forester's eye.

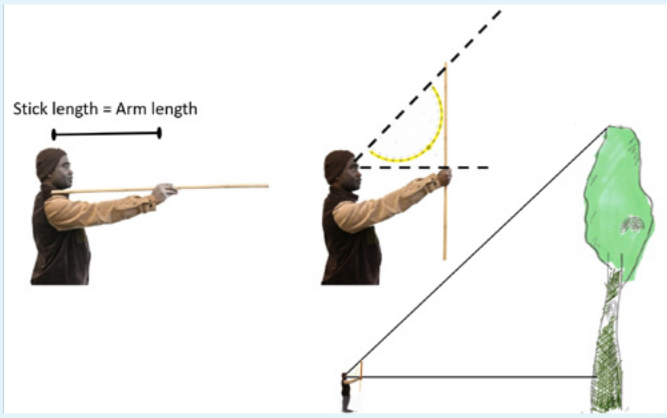

Figure 1: Application of the forester's triangle method
Image courtesy of Dr Andreas Schwarz

Materials

- Worksheet 1
- Tape measure or folding ruler and some string and a marker
- Tape, sticky notes, or other means to mark the tree without damaging it.
- Some sticks that are slightly longer than the students' arms
- A fairly large tree with enough space around it that the crown can be seen and you can walk the same distance

away as the tree's height; this might be in the schoolyard, a local street, or a park
- Objects to mark position (e.g. wooden blocks, stationary, rocks)
- Pencil and paper to record results

Procedure

Part 1 – Diameter at breast height (DBH)

1. Divide the students into groups of three. Small groups allow each student to be involved in measuring.
2. Students should measure the point on the trunk 1.3 m above the ground using the folding ruler or tape measure and mark this without damaging the tree (e.g., with a piece of tape).
3. They should then use the tape measure to measure the trunk circumference in cm at this point. Alternatively, they can wrap a piece of string around the tree and mark the points where the string ends touch, and then measure the length of the string between the marked points. Note this value on worksheet 1.
4. They can then use the following formula to calculate the diameter from the circumference:
   $d = C/\pi$
   where d=diameter and C=circumference.
5. Alternatively, younger students who aren't familiar with circle formulae can hold two sticks parallel on either side of the tree and measure the distance between them to get the diameter (figure 2).

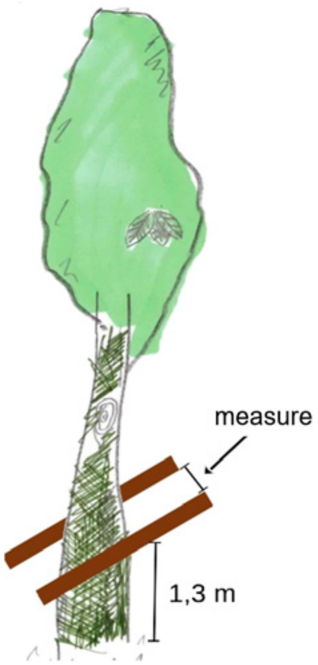

Figure 2: Measurement of the trunk DBH (1.3m)
Image courtesy of Dr Andreas Schwarz

Part 2 – Height

1. Still in their groups, students should read the forester's triangle instructions on worksheet 1.
2. One student should follow the instructions, holding the stick as described, and then walk backwards/forwards until the top of the stick lines up with the top of the tree. Another student should put a hand on their shoulder and make sure they do not walk into anything while walking backwards or focussing on the top of the stick.
3. The position on the ground should then be marked with an object.
4. The students should then measure the distance in m from the object to the tree trunk using the folding ruler or tape measure.
5. Ideally, each student should take a turn to make their own measurement and record the value in the worksheet. The height of the tree corresponds approximately to the distance between the forester and the tree.
6. Optional: ask students to look at the figure again. A distance is missing to determine the exact height of the tree. Which distance is it? Hopefully, some of them should see that the eye height of the forester should be added.
7. Optional: students can compare their values (as long as they are working on the same tree) and discuss the variation and possible sources of error.

Discussion

For younger students, it may be sufficient to know how the forester's triangle works, and to discuss the kind of triangles shown on the diagram and their basic properties (a right-angled isosceles triangle). But with older students, it may be valuable to explore the mathematical theory (intercept theorem) behind the forester's triangle by employing a mathematical simulation. For this, you can use the Intersect Theorem activity in the supporting material.

Activity 3 – Final calculation: how many trees?

Finally, the students can use their measurements (height and DBH) to determine the amount of CO_2 the tree has absorbed in its lifetime by employing estimation tables.

Broadleaf trees, such as beech and oak, generally grow more slowly than conifers (such as spruce or fir) and have denser and more complex vascular bundles, which makes them harder and heavier. This is why conifers are often referred to as softwoods and broadleaf trees are often referred to as hardwoods, although there is considerable variation between species. For this reason, separate estimation tables for conifer and broadleaf trees are given.

We offer two alternatives approaches:
1) Using worksheet 2, students first estimate the amount of carbon atoms fixed in the trunk and branches of the tree, and from that, they can then calculate the amount of absorbed CO_2.
2) In a simpler alternative, students use worksheet 3 to obtain the amount of CO_2 directly from the estimation table without further calculations.

Subsequently, the students can calculate how many trees of similar type/size/age would be needed to absorb the CO_2 produced by a flight of 2 × 1.343 km by dividing 680 (CO_2 released by the flight) by the amount of CO_2 having been absorbed by the measured tree.

This activity takes 20 minutes.

Materials

- Worksheet 2 (final calculation using carbon tables) or worksheet 3 (simplified version using CO_2 tables)
- Carbon estimation tables or CO_2 estimation tables (depending on the approach) for conifers and broadleaf trees
- Calculator

Procedure

1. Students need to identify whether the tree they measured is a conifer or broadleaf tree. Explain these terms to students if necessary.
2. Using the tree height and DBH measured in Activity 2, they should read off the carbon mass from the carbon estimation table and fill in the value on worksheet 2. Simpler option: for younger or less able students, they can read the CO_2 mass directly from the CO_2 estimation table instead and enter it on worksheet 3, and then proceed straight to step 5.
3. Remind students that this is the mass of carbon, and ask what would be needed to get the equivalent mass of CO_2 absorbed? Hint: compare the atomic mass of carbon with the molecular mass of CO_2. They should be able to calculate that the carbon mass should be multiplied by 3.67.
4. Students should then calculate the amount of CO_2 the tree had absorbed to build its aerial parts during its life (carbon mass from the table × 3.67).
5. Finally, they can calculate how many trees of similar type/size/age would be needed to absorb the CO_2 produced by a flight of 2 × 1343 km by dividing 680 (CO_2 released by the flight) by the CO_2 amount calculated in Step 4, or read from the CO_2 mass estimation table.

Image courtesy of Tamaryin Godinho

Discussion

The results can be used as a basis for discussion or further research/class projects on a number of themes. Possible questions include the following:

- This calculation only includes the above-ground parts of a tree. How much of a tree's biomass is underground?
- How old is the tree/how long would it have taken to absorb that much CO_2? How would you find out? Is there a way to estimate this without harming the tree?
- What happens to this carbon when the tree dies? What about if the tree is used for heating? Or for paper/cardboard packing?
- Do all trees absorb similar amounts of CO_2, or does it depend on where they grow and on the surrounding conditions? When trees are planted to address deforestation, is it important what trees are used?
- What other environmental benefits do trees provide? Is there a difference between mature mixed forests and monoculture plantations?
- What other ecosystems absorb CO_2? How much CO_2 do these different ecosystems currently absorb.
- Which has the greatest environmental impact: protecting existing forests or planting more trees? What are the threats to the world's forests?

- What alternatives are there to flying? Do they release more or less CO_2 for the same journey distance? Which forms of transport are the most environmentally friendly?
- What aspects of our everyday life contribute to our carbon footprint? Which steps can we take personally to reduce our carbon footprint? What changes can reduce the carbon footprint of a school?

Overall, it is important that students understand how vital forests are for the planet and why we need to protect them, but they shouldn't come away with the simplistic idea that we can keep releasing CO_2 at the current rate and global warming can be solved by simply planting trees.

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Cutting-edge science: related EIROforum research

Institut Laue–Langevin (ILL)

NEUTRONS FOR SCIENCE

Are there other ways of capturing CO_2 from the atmosphere? Researchers are investigating a variety of possibilities at ILL! For example, salty water can act as a carbon sink, trapping CO_2 in deep saline aquifers with high pressures and temperatures. Scientists are in the process of studying what happens to this CO_2. Another exciting approach is to capture and re-use CO_2 by converting it into chemicals that are useful to make pharmaceutical drugs and other high-value products.

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Resources

- Introduce your students common terms for classifying trees and timber (broadleaf vs conifer, hardwood vs softwood).
- Listen to a podcast about travel and climate change.
- Discover why meaningful reforestation more than just planting trees
- Learn about the importance of protecting the forests we already have.
- Read about five ways to save forests.
- Watch a video about the problem with some tree-planting campaigns.
- Discover crucial difference between different types of tree-planting projects.
- Check out this National Geographic special issue on Saving Forests.

- Dive into an interactive tool for Exploring our Forests from the FAO.
- Explore some resources to bring the science of sustainability into the classroom: Philippsen M (2024) Sustainability in the classroom: teaching materials from Science on Stage. *Science in School* **66**.
- Read about the consequences of a planet without trees: Voak A (2016) A world without trees. *Science in School* **35**.
- Explore the effect of carbon dioxide on ocean chemistry with practical activities: Ribeiro CI, Ahlgren O (2021) An ocean in the school lab: carbon dioxide at sea. *Science in School* **55**.
- Discover the water footprint of different food choices: Kelly S (2020) Do you know your water footprint? *Science in School* **50**.
- Explore the leaf the pigments that play a role in photosynthesis: Tarragó-Celada J, Fernández Novell JM (2019) Colour, chlorophyll and chromatography. *Science in School* **47**: 41–45.
- Sketch graphs from 'story' videos of everyday events to boost your understanding of data visualization: Reuterswärd E (2022) Graphing stories. *Science in School* **58**.
- Read about the first land plants and how they changed our world: Streubel S (2023) When plants moved ashore and changed the planet. *Science in School* **64**.
- Learn about how trees affect the atmosphere: Harrison TG, Khan MAH, Shallcross DE (2022) How trees affect the climate: is it just through photosynthesis? *Science in School* **58**.
- Read about the beneficial effects of tree canopies: Guerrieri R (2019) The secret life of forests. *Science in School* **46**: 20–24.
- Read about the complex environmental effects of food packaging: Barlow C (2022) Plastic food packaging: simply awful, or is it more complicated? *Science in School* **56**.
- Discover how mealworms could offer a sustainable alternative source of animal protein: Bonin L, Jeran M (2024) Towards sustainable nutrition: could mealworms provide a solution? *Science in School* **66**.
- Read about the development of lab-grown meat substitutes: Noble M (2023) From Petri dish to plate: the journey of cultivated meat. *Science in School* **63**.

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Dr Tamaryin Godinho is the executive editor of Science in School. She is passionate about science and believes that evidence-informed decision-making is crucial for addressing today's challenges and building a better future.