Carbon mineralization and enhanced root crops are two carbon removal approaches that offer significant potential to capture and store carbon, provided investment in research, development, and deployment is scaled up over the coming decades to resolve significant known challenges facing both.

**Carbon Mineralization**

Carbon mineralization includes a number of approaches that aim to speed up natural reactions between carbon dioxide in the air and reactive sources, like silicates and rocks rich in calcium or magnesium, to form solid carbonate minerals (NAS 2018a). Proposed mineralization approaches vary widely in technology readiness, potential, cost, risks and barriers. One promising approach that yields a product of economic value is the mineralization of mined reactive rock for use in synthetic building and construction materials like aggregate used in concrete. Shifting one-third of the construction aggregate market to mineralized aggregate would remove 410 MtCO₂ per year* from the atmosphere.

**Potential Approaches for Surficial and In Situ Carbon Mineralization**

**Surficial Mineralization**

- Ambient CO₂ reacts with reactive material
- Production of synthetic building materials
- Application of ground material to crop fields
- Use of material in large-scale building projects (e.g. dams or levees)
- Possible applications of material
- Potential options for reactive materials
- Mined reactive rock
- Suitable mine tailings and/or industrial waste

**In Situ Mineralization**

- Example of a potential in situ approach that both captures and stores CO₂
- Pump to accelerate circulation through aquifer
- Mineralization of produced water at the surface
- Enhanced circulation of CO₂-bearing water
- Peridotite aquifer with CO₂-depleted water

*100 MtCO₂ is roughly equivalent to taking 21.7 million passenger vehicles off the road for a year (EPA 2018)
Additional research and field-testing is needed to better understand the feasible potential for other mineralization approaches—including spreading finely ground reactive rock dust on agricultural land (which may improve soil quality and crop yields in acidic soils) and in situ (below-ground) mineralization to provide an enhanced storage mechanism for direct air capture or point-source carbon capture and storage.

Initial estimates indicate mineralization has considerably lower costs than direct air capture for use with reactive mining and industrial waste, but increasing costs at larger scales due to the need to mine reactive minerals and overcome associated logistical constraints. Key unknowns for surficial mineralization relate to the potential scale of economically accessible source material, possible negative environmental effects, full life-cycle carbon impacts of scalable processes, and competitiveness with conventional products.

Roughly $25 million per year in federal research and development funding would help to clarify promising mineralization pathways and demonstrate approaches warranting further public investment and ultimately commercialization.

Enhanced Root Crops

Developing crops with more, deeper and larger roots could increase carbon sequestration in soils. Such enhanced root systems can deliver several benefits—like erosion control, improved soil quality and ability to plant on marginal lands—that could benefit farmers and consumers as well as the climate, especially as population and food demand continues to grow.

Enhanced root crops are for the most part in the early stages of development and require additional research to understand feasibility and carbon removal potential. Work is ongoing both to develop perennial versions of annual crop species as well as to use gene editing and genomic selection to transfer favorable root characteristics into different plants.

The potential of enhanced root crops, which is highly theoretical, is estimated to be up to 185 MtCO₂ per year* across the planted area of major U.S. crops (249 million acres) but depends on the extent of change in carbon input and root depth (Paustian et al. 2016; USDA 2019). This estimate assumes increases in root size and depth similar to perennial grasses, which have not yet been achieved in commercial crop breeds in the United States.

The main barriers associated with enhanced root crops include maintaining consistent yields (and taste) comparable to conventional crops and advancing the breeding process at a speed that would allow wide-scale deployment before 2050 across all major crop varieties. Other unknowns relate to public perception and uptake as well as cost of enhanced crop variety seeds.

The National Academies of Sciences (2018) recommends a research and development budget of $40–50 million per year, sustained over a decade or longer, to accelerate development of new or enhanced varieties for major crop types. An initial time-bound investment to achieve proof of concept may be appropriate before continuing such a program.

Theoretical Potential of Carbon Sequestration through Perennialization of Major Crop Species

![Graph showing theoretical potential of carbon sequestration through perennialization of major crop species.](image)

Sources: USDA (2019b); Chambers et al. (2016); Deng et al. (2016).