4.3.7.4 *Enhanced Weathering (EW) and Ocean Alkalinisation*

Weathering is the natural process of rock decomposition via chemical and physical processes in which CO_2 is spontaneously consumed and converted to solid or dissolved alkaline bicarbonates and/or carbonates (IPCC 2005). The process is controlled by temperature, reactive surface area, interactions with biota and, in particular, water solution composition. CDR can be achieved by accelerating mineral weathering through the distribution of ground-up rock material over land (Hartmann and Kempe, 2008; Wilson et al., 2009; Köhler et al., 2010; Renforth, 2012; ten Berge et al., 2012; Manning and Renforth, 2013; Taylor et al., 2016), shorelines (Hangx and Spiers, 2009; Montserrat et al., 2017) or the open ocean (House et al., 2007; Harvey, 2008; Köhler et al., 2013; Hauck et al., 2016). Ocean alkalinisation adds alkalinity to marine areas to locally increase the CO_2 buffering capacity of the ocean (González and Ilyina, 2016; Renforth and Henderson, 2017).

In the case of land application of ground minerals, the estimated CDR potential range is 0.72–95 $GtCO_2\ yr^{-1}$ (Hartmann and Kempe, 2008; Köhler et al., 2010; Hartmann et al., 2013; Taylor et al., 2016; Strefler et al., 2018) *(low evidence, low agreement*). Marine application of ground minerals is limited by feasible rates of mineral extraction, grinding and delivery, with estimates of 1–6 $GtCO_2\ yr^{-1}$ (Köhler et al., 2013; Hauck et al., 2016; Renforth and Henderson, 2017) (*low evidence, low agreement*). Agreement is low due to a variety of assumptions and unknown parameter ranges in the applied modelling procedures that would need to be verified by field experiments (Fuss et al., 2018). As with other CDR options, scaling and maturity are challenges, with deployment at scale potentially requiring decades (NRC, 2015a), considerable costs in transport and disposal (Hangx and Spiers, 2009; Strefler et al., 2018) and mining (NRC, 2015a; Strefler et al., 2018)[6].

Site-specific cost estimates vary depending on the chosen technology for rock grinding – an energy-intensive process (Köhler et al., 2013; Hauck et al., 2016) – material transport and rock source (Renforth, 2012; Hartmann et al., 2013), ranging from 15–40 USD tCO_2^{-1} to 3,460 USD tCO_2^{-1} (Schuiling and Krijgsman, 2006; Köhler et al., 2010; Taylor et al., 2016, *limited evidence, low agreement*; Figure 4.2). The evidence base for costs of ocean alkalinisation and marine enhanced weathering is sparser than the land applications. The ocean alkalinisation potential is assessed to be 0.1–10 $GtCO_2\ yr^{-1}$ with costs of 14– >500 USD tCO_2^{-1} (Renforth and Henderson, 2017).

The main side effects of terrestrial EW are an increase in water pH (Taylor et al., 2016), the release of heavy metals like Ni and Cr, and plant nutrients like K, Ca, Mg, P and Si (Hartmann et al., 2013), and changes in hydrological soil properties. Respirable particle sizes, though resulting in higher potentials, can have impacts on health (Schuiling and Krijgsman, 2006; Taylor et al., 2016); utilisation of wave-assisted decomposition through deployment on coasts could avert the need for fine grinding (Hangx and Spiers, 2009; Schuiling and de Boer, 2010). Side effects of marine EW and ocean alkalinisation are the potential release of heavy metals like Ni and Cr (Montserrat et al., 2017). Increasing ocean alkalinity helps counter ocean acidification (Albright et al., 2016; Feng et al., 2016). Ocean alkalinisation could affect ocean biogeochemical functioning (González and Ilyina, 2016). A further caveat of relates to saturation state and the potential to trigger spontaneous carbonate precipitation.[7] While the geochemical potential to remove and store CO_2 is quite large, *limited evidence* on the preceding topics makes it difficult to assess the true capacity, net benefits and desirability of EW and ocean alkalinity addition in the context of CDR.

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[5] Other pyrolysis products that can achieve net CO_2 removals are bio-oil (pumped into geological storages) and permanent-pyrogas (capture and storage of CO_2 from gas combustion) (Werner et al., 2018)

Figure 4.2:

Evidence on Carbon Dioxide Removal (CDR) abatement costs, 2050 deployment potentials, and key side effects. Panel A presents estimates based on a systematic review of the bottom up literature (Fuss et al., 2018), corresponding to dashed blue boxes in Panel B. Dashed lines represent saturation limits for the corresponding technology. Panel B shows the percentage of papers at a given cost or potential estimate. Reference year for all potential estimates is 2050, while all cost estimates preceding 2050 have been included (as early as 2030, older estimates are excluded if they lack a base year and thus cannot be made comparable). Ranges have been trimmed to show detail (see Fuss et al., 2018) for the full range). Costs refer only to abatement costs. Icons for side-effects are allocated only if a critical mass of papers corroborates their occurrence

Notes: For references please see Supplementary Material Table 4.SM.3. Direct Air Carbon Dioxide Capture and Storage (DACCS) is theoretically only constrained by geological storage capacity, estimates presented are considering upscaling and cost challenges. BECCS potential estimates are based on bioenergy estimates in the literature (EJ yr^{-1}), converted to $GtCO_2$ following footnote 3. Potentials cannot be added up, as CDR options would compete for resources (e.g., land). SCS - Soil Carbon Sequestration; OA - Ocean Alkalinisation; EW- Enhanced Weathering; DACCS - Direct Air Carbon Dioxide Capture and Storage; BECCS - Bioenergy with Carbon Capture and Storage; AR - Afforestation