Environmental life cycle assessment of CO_2 sequestration through enhanced weathering of olivine

-Working paper-

Joris Koornneef*, Evert Nieuwlaar
Group Science, Technology & Society
Copernicus Institute
Utrecht University

Introduction and Goal

Recently, Schuiling and Krijgsman (2006) have proposed an option to sequester atmospheric carbon dioxide through enhanced weathering of olivine or calcium silicates. One option considered is the spreading of finely grinded olivine on farmland or forestland. They also state that the reaction of olivine with CO_2 in the presence of water yields magnesium-carbonate, amorphous silica and an iron-oxide, i.e. harmless byproducts. The main product of the reaction is off course the removal of CO_2 from the atmosphere. However, merely describing the equation for the chemical reaction does not take into account the fact that the mineral has to be mined and pre-treated in order to enhance its weathering. These processes require energy and as a consequence CO_2 will be emitted. To verify whether enhanced weathering will result in a net reduction of CO_2 emissions, it is important that a greenhouse gas balance is constructed. This greenhouse gas (GHG) balance will include the emissions of CO_2 in the whole life cycle of this option. This means that CO_2 emissions during mining, transport, grinding and spreading of the olivine at the sequestration site will be included in the GHG balance. In this study such a balance will be presented.

Furthermore, there are also other environmental impacts attached to processes in the life cycle of this option, e.g. the emission of acidifying or eutrophying substances. The potential environmental impacts over the whole life cycle can be assessed with a life cycle assessment. Then, it is also possible to compare the olivine sequestration option with life cycle assessments of other CO_2 mitigation options. The second goal of this study is to scan for environmental impacts in the life cycle of the olivine CO_2 sequestration option and compare the option with the capture of CO_2 from the flue gasses of a coal fired power plant. Finally other issues related to CO_2 mitigation through enhanced weathering of olivine are discussed briefly.

Functional unit

The unit which is used to compare the CO_2 mitigation options is: the prevention of 1 tonne Greenhouse Gas equivalents[1] having an impact on climate change.

Geographical scope

This study assumes the enhanced weathering of olivine on the Dutch coast. The geographical scope of the data for the life cycle inventory agrees with this assumption, i.e. predominantly data valid for Europe is used. This option is chosen as olivine reacts with CO_2 when dissolved in water. The availability of water is thus a primary condition.

Methodology and life cycle inventory

Both the GHG balance as the environmental impacts of the options are assessed using the SimaPro Life Cycle Assessment software.

---

*corresponding author: j.m.koornneef@uu.nl

[1] This is expressed in CO_2 equivalents.

Given the prospective nature of this assessment and the associated uncertainty in the assumptions the uncertainties of the outcome should be carefully dealt with. Therefore, in this study four scenarios for CO_2 mitigation through enhanced weathering of olivine have been developed. These encompass the local spreading, distant spreading, optimistic and conservative scenario. These scenarios indicate the range of outcomes possible when varying the main assumptions. The main assumptions for the four scenarios are presented in Table 1.

In Figure 1 the product system analyzed in this study is shown. It incorporates the mining of the olivine. We have assumed a dolomite mine as a proxy for the environmental impacts of olivine mining. The environmental interventions associated with mining are derived from (Ecoinvent Centre accessed 2007).

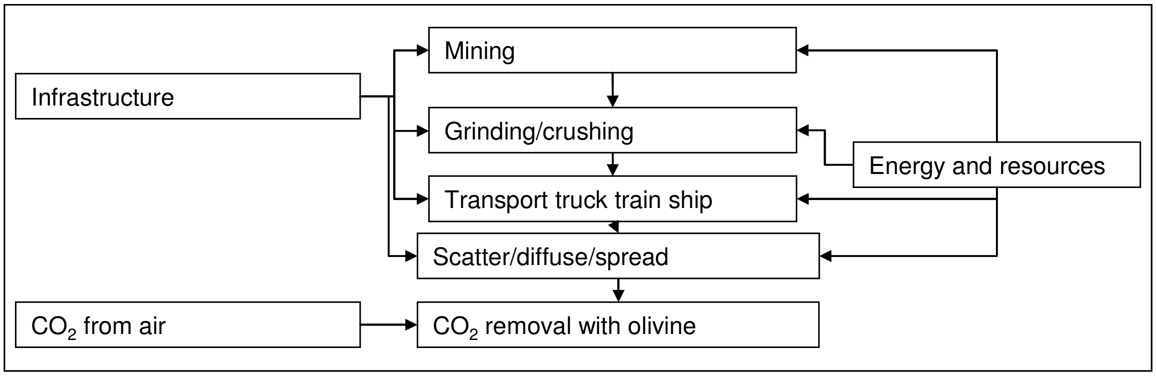

Figure 1- The olivine product system analyzed in this study.

After mining, the olivine undergoes crushing and grinding to obtain a grain size suitable for enhanced weathering within a foreseeable timeframe. In Figure 2 the relationship between reaction time and the fraction of olivine reacted is shown. This reaction time depends mainly on de rate of dissolution, the molar density and particle size.

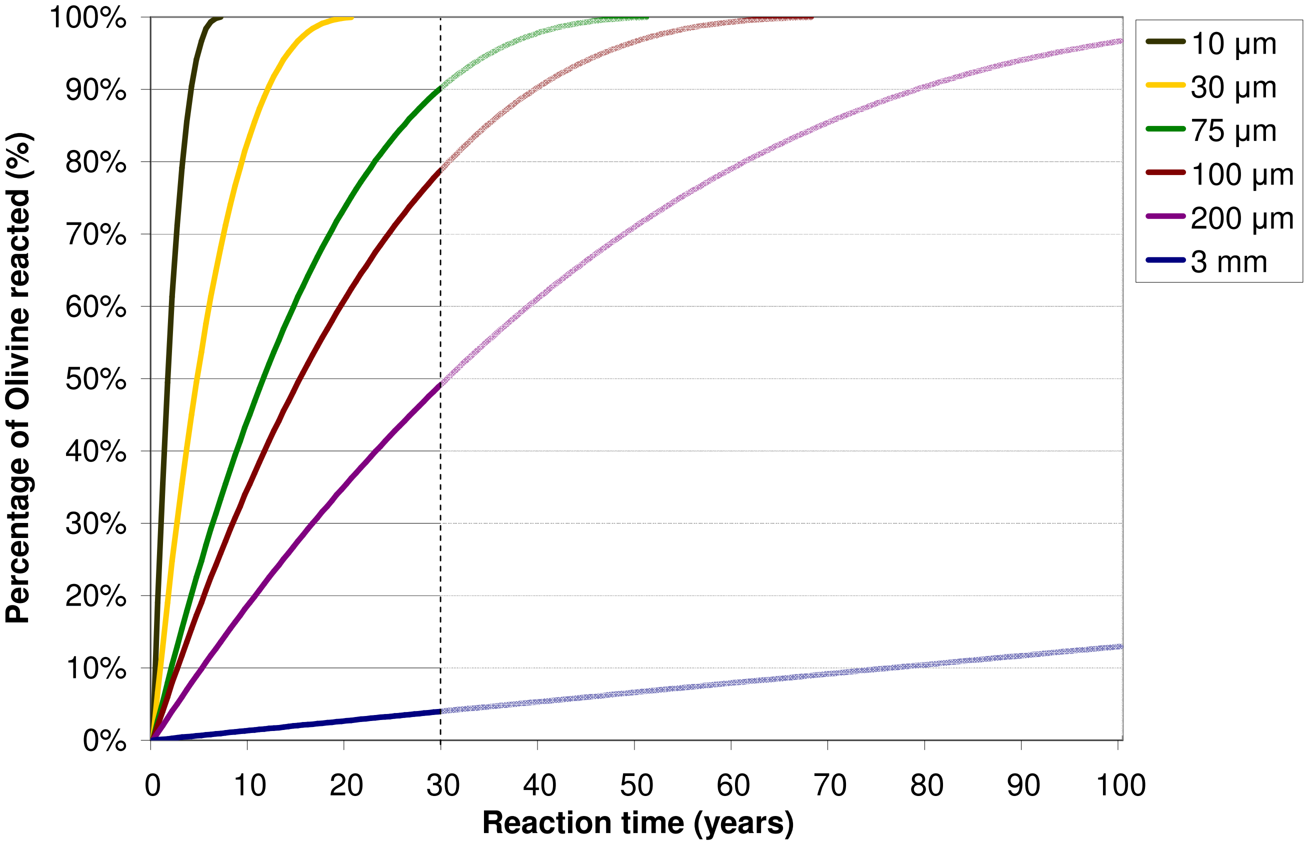

Figure 2 -Relationship between reaction time and percentage of olivine reacted for various particle diameters. For the calculation it is assumed that the olivine particle shrinks as it reacts with the (dissolved) CO_2 according to the shrinking particle model, see Appendix 1. The rate of dissolution is assumed to be $6.0*10^{-8}$ moles*m^{-2}*$minute^{-1}$ and molar density is assumed to be 23245 mol/m^3 . This is the dissolution rate that corresponds to a pH found in soil and rainwater (Hangx and Spiers 2009).

For this study we assume that a considerable share, i.e. >90%, of the olivine should have reacted within 30 years. This encompasses the crushing and grinding of the olivine to a particle size of approximately 75 µm (see Figure 2). Schuiling (2009) argues that in nature reaction rates of 10 micron per year are common and that 20 micron per year is also possible. Higher reaction rates may be possible with lower pH values in for instance the soil. Organisms may act as a catalyst by lowering soil pH through the release of acid substance.

The crushing and grinding is an energy intensive process. Furthermore, the energy requirement increases more than linear when going to smaller particle diameters (Khoo and Tan 2006; Gerdemann et al. 2007). Decreasing the time needed for the removal of CO_2 from the atmosphere with olivine to take place thus comes with additional energy requirement. The energy requirement for crushing and grinding is an important parameter that is varied in the scenarios, see Table 1. In the distant and local spreading scenarios we assume a grain size of ~75 µm to be enough. In the optimistic scenario no grinding is assumed. In the conservative scenario grinding up to ultra-fine grain sizes (i.e. 10 µm) is assumed. The electricity required for crushing and grinding is assumed to be the average electricity mix of the UCTE[2].

---

[2] In this case the UCTE includes the countries: Belgium, Germany, Spain, France, Greece, Slovenia, Croatia, Bosnia Herzegovina, Serbia and Montenegro, Macedonia, Luxembourg, the Netherlands, Portugal and Switzerland.

After crushing and grinding, the olivine is transported by ship and truck to the sequestration site where it is spread. There the reaction with the CO_2 is assumed to take place (see Appendix 2 for mineral reactions that may occur). For this reaction it is assumed that 1 kg of olivine is needed to sequester 1 kg of CO_2. This value represents an relative moderate optimistic value within the range of values mentioned in literature between 0.8 and 2 tonne olivine per tonne CO_2 removed from the atmosphere (Khoo and Tan 2006; Gerdemann, O'Connor et al. 2007; Hangx and Spiers 2007; Hartmann and Kempe 2008). Both the lower and higher end of this range is used in the optimistic and conservative scenarios, respectively.

Table 1 Main assumptions for the four scenarios developed in this study.

Process	Unit	Local spreading	Distant spreading	Optimistic	Conservative
Crushing and grinding					
primary crushing (>100 µm)	kWh/t olivine	2	2	2	2
primary grinding (75 µm)	kWh/t olivine	11	11	-	11
secondary grinding (38 µm)	kWh/t olivine	-	-	-	70
tertiary grinding (10 µm)	kWh/t olivine	-	-	-	150
Ship transport*	t*km	0	1200	0	3500
Truck transport**	t*km	300	150	50	150
Olivine requirement***	t olivine/ t CO_2 removed	1	1	0.8	2

*Transport distance from Olivine mine to Rotterdam harbour (1200 for Norway, 3500 for Greenland, 0 for on site spreading)

**Transport distance for truck transport from Rotterdam to the Dutch west coast. Assuming that olivine is spread on the Dutch west coast; from Den Helder to Breskens (both at approx. 150 km from Rotterdam harbour). 300 km is assumed for near mine mouth spreading in the local spreading scenario. For near mine mouth spreading 50 km is assumed in the optimistic scenario.

***Hangx and Spiers (2007) have summarized various possible reactions between olivine and CO_2 and showed that a range between 0.8 and 2 kg of olivine per kg CO_2 sequestered is possibly required. From Hartmann and Kempe (2008) a ratio of 1.6 kg olivine per kg CO_2 sequestered could be derived. See also Appendix 2.

Results

Greenhouse gas balance

In Table 2 the greenhouse gas balance is presented for the enhanced weathering of olivine as CO_2 mitigation option. With the assumptions above we have calculated that in order to avoid 1 tonne of CO_2 equivalents (CO_2 eq.) having an impact on climate change, depending on the scenario, 1010 to 1555 kg of CO_2 has to be sequestered by the reaction with olivine. This requires 808 to 3110 kg of pure olivine to react with CO_2.

The GHG reduction efficiency for the four scenarios is found to be between 64% and 99% considering the full life cycle. The main contributor to life cycle GHG emissions is the process of electricity generation for crushing and grinding of olivine and to a lesser extent ship and local truck transport (see Table 2). It is shown that the local spreading scenario scores lower on the life cycle reduction efficiency compared to the distant spreading scenario. This is the result of ship transport having a relative lower carbon footprint than truck transport.

During pre-treatment, the tertiary grinding step in the conservative scenario consumes a significant amount of electricity (i.e. 150 kWh /tonne olivine) and therefore contributes the most (over 40%) to life cycle GHG emissions. The other scenarios include less pre-treatment processes and show significant higher GHG reduction efficiencies. Size reduction of the olivine is thus a crucial step in the life cycle. It determines both to a large extent the GHG reduction efficiency as well as the amount of years needed for the reaction to conclude. A clear trade-off is thus shown by this assessment between reaction time and GHG reduction efficiency.

Table 2- Greenhouse gas balance for CO_2 sequestration by enhanced weathering of olivine (in kg CO_2 equivalents)

Process	Scenario			
	Local spreading	Distant spreading	Optimistic	Conservative
Mining	0	0	0	1
Primary Crushing	1	1	1	3
Primary grinding	6	6	-	17
Secondary grinding	-	-	-	105
Tertiary grinding	-	-	-	226
Ship transport	-	13	-	115
Truck transport	53	26	7	78
Olivine loading and spreading	3	3	2	9
$CO_{2\ removed}$*	-1063	-1049	-1010	-1555
Net avoided	1000	1000	1000	1000
Life cycle reduction efficiency (CO_2 eq. $_{avoided}$ / CO_2 eq. $_{removed}$)	94%	95%	99%	64%

Note that figures may not add up due to rounding.
*this is the amount of CO_2 that is assumed to be net removed from the atmosphere through the reaction with olivine. This should not be mistaken with the amount of CO_2 that has reacted with the olivine.

Comparison against alternative CO_2 mitigation option

Here the three scenarios are compared to another CO_2 mitigation option: Carbon Capture and Storage (CCS). This option encompasses the capture of CO_2 at a coal fired power plant using post-combustion capture including transport and storage in a geological reservoir[3]. The complete life cycle assessment of this option is shown and discussed elsewhere (Koornneef et al. 2008).

The five scenarios (four by enhanced weathering of olivine and one CCS option) are compared on environmental impacts other than climate change, as the impact (i.e. avoidance of 1 tonne CO_2 eq.) on climate change is the basis of comparison.

Results depicting the impact on other environmental themes are shown in Figure 3. In the figure the worst case is set to 100% to make comparison per impact category (abiotic depletion, ozone layer depletion, human toxicity, ecotoxicity categories, photochemical oxidation, acidification and eutrophication) possible. In Table 3 the accompanying data is presented. The results indicate that the conservative scenario for mitigation with olivine is the worst option for all environmental impact categories. A more benign scenario is the CCS scenario. This scenario results however in higher environmental impacts compared to the optimistic, and local and distant spreading scenarios for all environmental impact categories except marine aquatic ecotoxicity. All scenarios except the conservative olivine scenario outperform the CCS scenario in particular in the impact categories abiotic depletion, human toxicity and eutrophication. The optimistic olivine scenario is by far the most

---

[3] This encompasses a state-of-the-art coal fired power plant equipped with a post-combustion capture facility based on chemical absorption of CO_2 with monoethanolamine (MEA)

environmental benign scenario and scores between the optimistic and conservative scenario differ orders of magnitude.

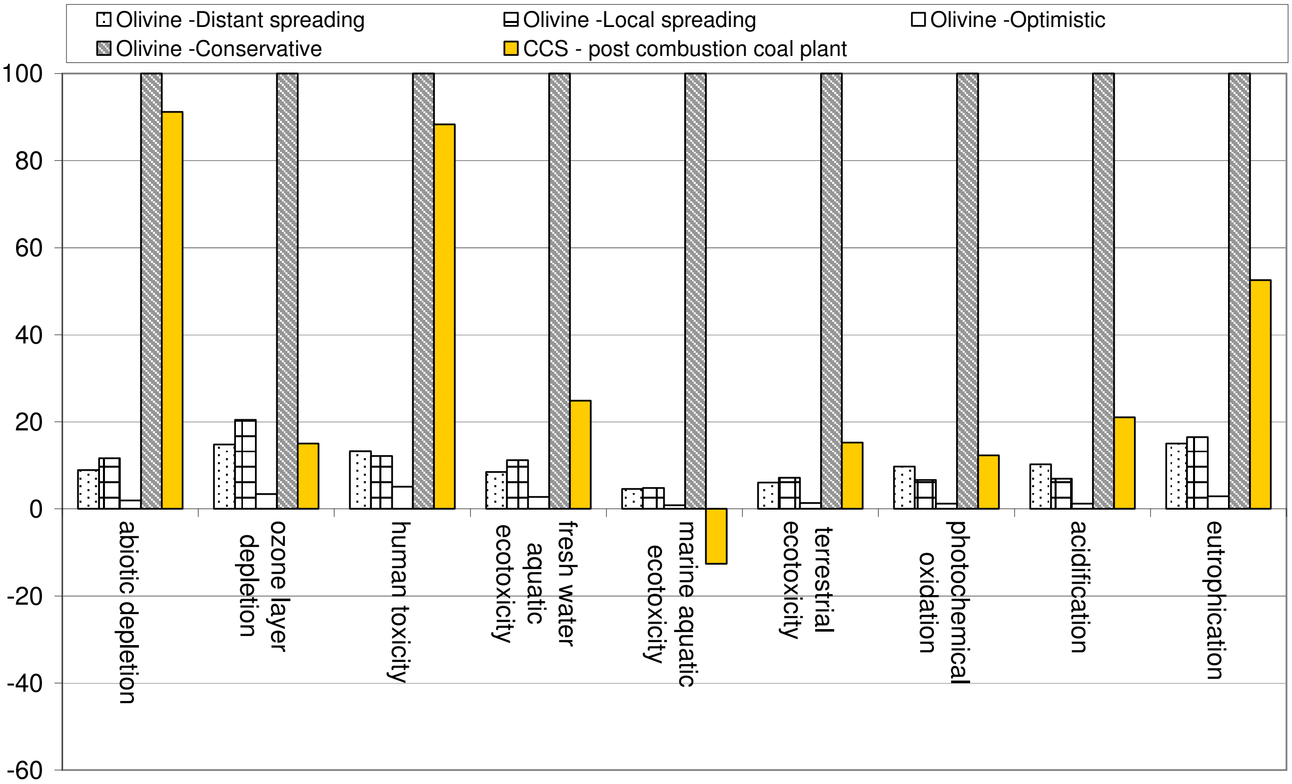

Figure 3 Comparison of 1 tonne GHG emission mitigation through enhanced weathering with olivine (4 scenarios: distant spreading, local spreading, optimistic and conservative) and through CO_2 captured from a coal fired power plant (right colored bars) derived from (Koornneef, van Keulen et al. 2008). Note that all environmental impact scores are indices with the most malign score set at 100.
Method used: CML 2 baseline 2000 V2.03

Table 3 Results of the comparison between enhanced weathering with olivine and CO_2 capture from a coal fired power plant

Environmental Impact category	Unit	Olivine				CCS
		Local spreading	Distant spreading	Optimistic	Conservative	
abiotic depletion	kg Sb eq.	$4.6*10^{-1}$	$3.5*10^{-1}$	$7.6*10^{-2}$	3.9	3.6
ozone layer depletion	kg CFC*-11 eq.	$8.1*10^{-6}$	$5.8*10^{-6}$	$1.3*10^{-6}$	$4.0*10^{-5}$	$5.9*10^{-6}$
human toxicity	kg 1,4-DB** eq.	24.4	26.7	10.2	$2.0*10^{2}$	$1.8*10^{2}$
fresh water aquatic ecotoxicity	kg 1,4-DB** eq.	3.2	2.4	$7.7*10^{-1}$	28.5	7.1
marine aquatic ecotoxicity	kg 1,4-DB** eq.	$1.3*10^{4}$	$1.3*10^{4}$	$2.4*10^{3}$	$2.7*10^{5}$	$-3.4*10^{4}$
terrestrial ecotoxicity	kg 1,4-DB** eq.	$1.5*10^{-1}$	$1.2*10^{-1}$	$2.7*10^{-2}$	2.1	$3.1*10^{-1}$
photochemical oxidation	kg C_2H_4 eq.	$1.2*10^{-2}$	$1.8*10^{-2}$	$2.1*10^{-3}$	$1.9*10^{-1}$	$2.3*10^{-2}$
acidification	kg SO_2 eq.	$3.7*10^{-1}$	$5.4*10^{-1}$	$6.2*10^{-2}$	5.3	1.1
eutrophication	kg PO_4 eq.	$6.8*10^{-2}$	$6.2*10^{-2}$	$1.2*10^{-2}$	$4.1*10^{-1}$	$2.2*10^{-1}$

*CFC = chlorofluorocarbon
**1,4-DB = 1.4-dichlorobenzene

Process contribution

The contribution of process, or groups of processes, in the life cycle of the distant spreading olivine scenario is shown in Figure 4. The main contributors to the scores for the environmental impact categories are the transport of olivine and electricity generation for the crushing and, in particular, grinding of the olivine. The scores for the ecotoxicity categories are to large extent determined by the electricity generation needed for the crushing and grinding. Transport by truck and ship is the dominant process for the scores for acidification, eutrophication and photochemical oxidation. This is due to the emissions of NO_x and SO_x in the life cycles for truck and ship transport. Transport by truck is the most contributing process in six out of ten impact categories (abiotic depletion, climate change, ozone layer depletion, fresh water aquatic ecotoxicity, terrestrial ecotoxicity and eutrophication) followed by ship transport which is dominant in three (human toxicity, photochemical oxidation and acidification). This explains the difference between the local and distant spreading scenario shown in Figure 3. The processes in the life cycles needed for mining and loading and spreading of the olivine contribute considerably less to most impact categories. Mining has however a share in the score for human toxicity of about 27%. This is due to the dust (i.e. particulate matter < 10 µm) emissions as a result of the mining process. Crushing and grinding contributes heavily to the score for marine aquatic ecotoxicity. This is primarily due to the emission of hydrogen fluoride[4] during electricity production that is required for crushing and grinding.

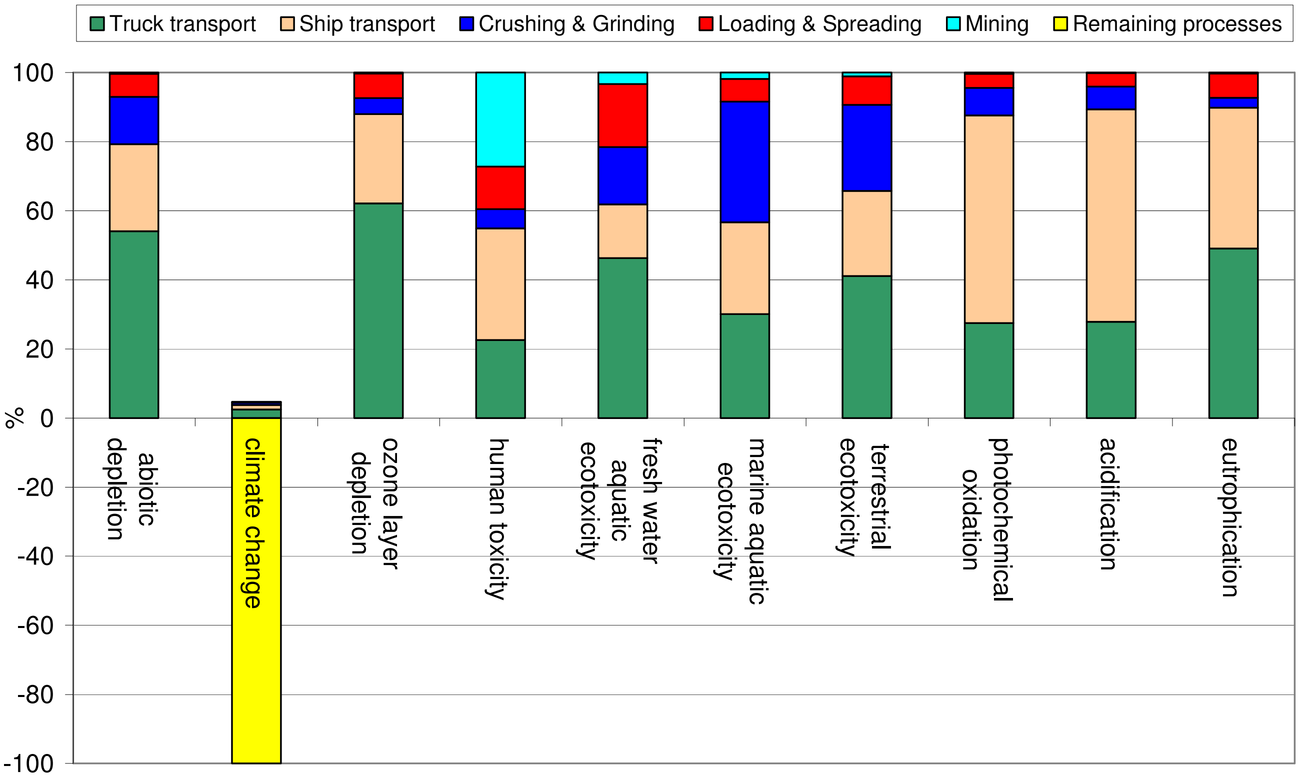

Figure 4 Contribution of (groups of) processes to the scores for environmental impact categories for the distant spreading olivine scenario.

---

[4] In literature characterization factors for hydrogen fluoride emissions used in the CML impact assessment method have been a point of discussion. It is suggested by several authors that they are possibly too high, which consequently will result in an overestimation of the potential environmental impact of HF emissions and to a dominance of these emissions in the contribution to the total score for marine aquatic ecotoxicity (Frischknecht R. et al. 2004; Heijungs et al. 2007; Koornneef, van Keulen et al. 2008).

Discussion

Possible improvements

The largest share of the scores for the environmental impact categories (including the GHG balance) can be attributed to the energy requirement for crushing and grinding and for the transport of the olivine (see Table 2 and Figure 4). The impact of the chosen electricity mix on the environmental profile of sequestration with olivine is thus considered to be high. This entails that the sensitivity of the results to this assumption is likely to be large. Lowering the environmental impact of the energy requirement can then be done by fulfilling the energy demand with renewable energy technologies that result, in general, in lower environmental impacts. Another possible improvement is the reduction of the energy requirement in order to lower the environmental impacts and improve the GHG reduction efficiency. Another lesson that can be drawn is that transport should be limited as much as possible and should be performed with relative clean transport technologies, i.e. with a focus on renewable transport fuels. To ensure that transport requirement is minimised, the spreading of olivine should take place as close to olivine deposits as possible. These deposits can be found around the world (Schuiling and Krijgsman 2006; Kramer 2007). The deposits in warmer climates deserve attention as higher temperatures means enhancement of the kinetics of the reaction. The geographical scope of the data used in this study entails that the results of this study may not be valid for those other regions. Where possible region specific life cycle inventory data should be used when performing a LCA for the enhanced weathering of olivine in those regions.

The reaction time needed for a considerable share of the olivine to have reacted with the CO_2 is a crucial assumption. It determines to a large extend the optimal particles size and with it the environmental performance of this option. It may also have administrative consequences. For instance, some form of monitoring is required if the amount of CO_2 avoided through enhanced weathering is included as an option in the Emission Trading Scheme (ETS). For large olivine particles with possibly several decades of reaction time this will mean a problem for the allocation of ETS certificates. For instance, an important question is: ”When will the certificates be allocated? During the project duration of spreading the olivine? Or after all olivine has reacted? And how should it be measured? These issues should also be tackled if this option is considered part of our portfolio to mitigate climate change.

Environmental impacts not included in the life cycle assessment

A possible issue associated with enhanced weathering of olivine is that of dust emissions. In the conservative case the olivine is grinded to a size of approximately 10 μm. This finely grinded olivine can also be considered as particulate matter though is not included as such in the current assessment. If the olivine would be considered as such and included in the assessment, then the score for human toxicity for the scenario that include fine grinding would be significantly higher. Fine particulate matter may namely have severe impact on human health as it is believed to be an important factor in human respiratory diseases. The actual impact of finely grinded olivine on human heath is however currently unknown.

In addition, other important possible environmental impacts are also not included in the LCA. These are the disturbance (light and noise emissions) of the areas where the olivine is mined, transported and spread. Land degradation might be another negative consequence of mining and transport operations. The spreading of olivine may however also have positive consequences. Olivine spreading is currently being used as mineral fertilization “to improve the quality of soil water, to increase crop productivity, or to prevent plant diseases” (Hartmann and Kempe 2008). Such land upgrading may reduce the demand for other fertilisation options and with it reduce environmental impacts of for instance crop growth. These environmental impacts (both trade-offs and benefits) are not included in this study but may prove to be important and as such deserve more attention in further research.

Cost

Hangx and Spiers (2007) have estimated that this option will cost between the 1.08 and 33.52 Euro per tonne of CO_2 avoided. These values are merely based on electricity production cost. This means that other (transport, infrastructure etc) cost factors are not included, resulting in an underestimation of the costs. Furthermore, the large variance in the cost estimate is the consequence of the size of the olivine particle. The lower bound of the estimate represents CO_2 sequestration with olivine with a particle size of 3 mm. The higher end of the estimate represents ultra fine grinded (10 µm) olivine to react wit the CO_2. These results clearly indicate that there is also an important trade-off between economical and energetic performance and the duration of the reaction.

Production capacity

A potential bottleneck for enhanced weathering of olivine is the current worldwide production rate of olivine. The US geological survey has estimated that the annual production of olivine is about 8 Mt (Kramer 2007). This means that if the current annual production of olivine would be entirely used to sequester CO_2, that this would be enough to compensate the CO_2 emissions of approximately one coal fired power plant, according to the assumptions used in this study. Large scale implementation of this option would thus require a massive increase in the annual mining capacity of olivine. The mining of olivine would then become the 3rd largest mining sector in the world, according to (Schuiling 2009).

Conclusions

Concluding, CO_2 mitigation by enhanced weathering of olivine might be an attractive option considering the greenhouse gas mitigation efficiency and other environmental impacts. Prerequisites for this conclusion are that the transport of olivine is limited to regional transport and that the energy requirement for crushing and grinding is significantly reduced as these are important factors in environmental performance of this option. Minimizing the grinding of olivine holds that longer reaction times should be accepted, i.e. 30 years and longer.

A trade-off is namely expected between the reaction time of the olivine and the environmental performance, including GHG reduction efficiency. This efficiency is calculated to be between 64% and 99% for the conservative and optimistic set of assumptions, respectively. The comparison of four scenarios with enhanced weathering of olivine with another CO_2 mitigation option, CCS from a coal fired power plant, yielded that the conservative set of assumptions for the olivine options is outperformed by the CCS option. The remaining scenarios with more optimistic assumptions for the olivine option in turn outperform the CCS case on seven out of nine environmental impact categories; the distant spreading and optimistic scenario outperforms CCS on eight categories.

The scores for the environmental impact categories vary orders of magnitude between the optimistic and conservative scenario. This is caused by the large uncertainty for input values for dominant assumptions, i.e. the amount of olivine, transport and energy required.

Not all relevant environmental impacts have been addressed in life cycle assessment and are as such included in the results. Examples of these impacts are the increase of atmospheric particulate matter due to spreading of olivine and the possible degradation and disturbance of areas as a result of olivine mining and transport. Also the possible upgrade and fertilization effect of olivine on the soil is not included. Non environmental issues that are addressed briefly in this study suggest that monitoring of avoided CO_2 emissions and the global reduction capacity of this option are possible bottlenecks.

Appendices

Appendix 1 Shrinking particle model (after (Levenspiel 1972))

$$1-(1-X)^{1/3}=\frac{R}{\rho * \mathrm{d}} * t$$

X = fraction reacted
R = rate of dissolution (6.0 $*10^{-8}$ moles$*$m$^{-2}*$minute^{-1})
ρ = molar density (23245 mol/m^3)
d = particle size (10, 30, 75, 100, 200 μm and 3 mm)
t = reaction time in minutes

Appendix 2 Mineral reactions in literature

$Mg_2SiO_4 + 4CO_2 + 4H_2O \rightarrow 2Mg^{2+} + 4HCO3^- + H_4SiO_4 \rightarrow 2MgCO_3 + SiO_2 + 2CO_2 +2\ H_2O$ (from (Hartmann and Kempe 2008)

$(Mg,Fe)_2SiO_4 + 4CO_2 + 4H_2O \rightarrow 2(Mg,\ Fe^{2+}) + 4HCO_3^- + H_4SiO_4$ (from (Schuiling and Krijgsman 2006)

References

Ecoinvent Centre (accessed 2007). Ecoinvent data v1.2. as implemented in SimaPro software v 7.0. Dübendorf, Swiss Centre for Life Cycle Inventories,.
Frischknecht R., Jungbluth N., et al. (2004). Implementation of Life Cycle Impact Assessment Methods. Final report ecoinvent 2000 No. 3, ,. Dübendorf, Switzerland. , Swiss Centre for Life Cycle Inventories.
Gerdemann, S. J., W. K. O'Connor, et al. (2007). "Ex Situ Aqueous Mineral Carbonation." Environmental Science & Technology **41**(7): 2587.
Hangx, S. J. T. and C. J. Spiers (2007). Direct carbonation of olivine under Earth surface conditions as a solution for reducing CO2 emissions - a literature review and preliminary evaluation, HPT Laboratory, Department of Earth Sciences, Utrecht University.
Hangx, S. J. T. and C. J. Spiers (2009). "Coastal spreading of olivine to control atmospheric CO2 concentrations: a critical analysis of viability." International Journal of Greenhouse Gas Control **in press**.
Hartmann, J. and S. Kempe (2008). "What is the maximum potential for CO2 sequestration by “stimulated” weathering on the global scale?" Naturwissenschaften.
Heijungs, R., J. Guinée, et al. (2007). "Bias in normalization: Causes, consequences, detection and remedies." The International Journal of Life Cycle Assessment **12**(4): 211.
Khoo, H. H. and R. B. H. Tan (2006). "Life cycle evaluation of CO_2 recovery and mineral sequestration alternatives." Environmental Progress **25**(3): 208-217.
Koornneef, J., T. van Keulen, et al. (2008). "Life cycle assessment of a pulverized coal power plant with post-combustion capture, transport and storage of CO2." International Journal of Greenhouse Gas Control **2**(4): 448.
Kramer, D. A. (2007). 2006 Minerals Yearbook - Magnesium Compounds, U.S. Geological Survey.
Levenspiel, O. (1972). Chemical reaction engineering. . New York, John Wiley and Sons.
Schuiling, R. (2009). Personal communication of reaction rates for olivine in nature. J. Koornneef. Utrecht.
Schuiling, R. and P. Krijgsman (2006). "Enhanced Weathering: An Effective and Cheap Tool to Sequester Co2." Climatic Change **74**(1): 349.