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Economic Ripple Effects of Large-Scale Basalt Enhanced Weathering in the Philippines

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Carbon dioxide removal using negative emissions technologies will be needed to achieve net zero greenhouse gas emissions. Enhanced weathering is a negative emissions technology that relies on the acceleration of natural geochemical reactions between alkaline rocks or minerals with carbon dioxide and water. It results in the permanent sequestration of carbon as bicarbonate ions in runoff water. Under some conditions, this technique can also give secondary co-benefits, such as improving the suitability of acidic soil for agriculture. However, large-scale enhanced weathering will require ramping up the activity in the mining, transportation, and electricity generation sectors. In this work, the potential economic effects of large-scale basalt-enhanced weathering in the Philippines are estimated using input-output analysis. The results show that offsetting 20 % of the country's carbon dioxide emissions requires substantial direct increases in quarrying, land transport, and power generation, coupled with smaller changes in other sectors via indirect ripple effects.

1. Introduction

It is now apparent that large-scale CO_2 removal (CDR) will be needed to achieve net zero greenhouse gas (GHG) emissions by mid-century and limit temperature rise by 2100 to well below 2 °C (Intergovernmental Panel on Climate Change, 2022). CDR can be achieved using negative emissions technologies (NETs) that rely on different pathways for sequestering carbon that is fixed from atmospheric CO_2. The technology spectrum ranges from engineered NETs such as direct air capture (DAC) and bioenergy with carbon capture and storage (BECCS) to nature-based CDR such as afforestation and soil carbon sequestration (Smith et al., 2019). Most NETs rely on photosynthesis as the initial carbon fixation step, with the notable exceptions of DAC and enhanced weathering (EW), which relies on the artificial acceleration of naturally occurring geochemical reactions.

CDR via the engineered enhancement of the reaction of CO_2 and water with alkaline minerals was first proposed by Seifritz (1990). Ex situ EW involves applying powdered rocks or minerals on land at a rate calibrated based on average local rainfall and temperature data (Strefler et al., 2018). Rocks which contain silicate minerals react with atmospheric CO_2 in the presence of water, resulting in soluble bicarbonate ions; for example, calcium silicate weathers following the reactions indicated in Eq(1). The geochemical reactions lead to partial dissolution of the powder; carbon in the bicarbonate ions in the runoff water is eventually carried into the oceans for permanent sequestration. In addition to naturally occurring materials, different kinds of alkaline industrial waste can also be used (Renforth, 2019). Although EW can be done purely for CDR on marginal land, its use in conjunction with conventional (Beerling et al., 2020) or urban (Haque et al., 2021) agriculture can give significant co-benefits due to improvement of soil quality. EW can also be done in remote terrestrial ecosystems by spreading rock dust from aircraft (Goll et al., 2021) or in coastal environments (Meysman and Montserrat, 2017).

$$\mathrm{CaSiO_3} + 2\mathrm{CO_2} + \mathrm{H_2O} \rightarrow \mathrm{Ca^{2+}} + 2\mathrm{HCO_3^-} + \mathrm{SiO_2} \quad (1)$$

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There are major challenges in ramping up NETs such as EW from laboratory or demonstration scale to meet the projected CDR demand in the order of multiple Gt/y (Nemet et al., 2018). Large-scale deployment of NETs can result in substantial environmental impacts or co-benefits, which cannot be ignored (Smith et al., 2019). Models will be needed to understand how the introduction of large-scale EW-CDR will affect the background technosphere (Tan and Aviso, 2021). Life-cycle assessment (LCA) and related methods can be used to gauge the direct and indirect effects of EW-CDR. Because of the high energy demand of grinding down rocks and minerals into powder form, Eufrasio et al. (2022) found that the local electricity mix is critical in determining the effectiveness of EW-CDR. Researchers have also examined the trade-offs involved in varying particle sizes for both terrestrial (Rinder and von Hagke, 2021) and coastal (Foteinis et al., 2023) EW-CDR systems. Lefebvre et al. (2019) used LCA to study the viability of basalt-based EW-CDR in Brazil. Jerden et al. (2024) developed a hybrid geochemical and LCA model for EW-CDR systems. Oppon et al. (2023) used a multi-region input-output (MRIO) model to gauge the economic and environmental effects of increased basalt production for EW-CDR; however, this incremental output was imposed exogenously without the creation of a separate EW-CDR sector in the economic system. No work to date has reported an approach that includes the insertion of a new CDR sector into an input-output model.

To address this research gap, an environmentally-extended input-output (EEIO) model is developed here based on the general formulation of Leontief (1970). This approach involves adding an extra row for CO_2 emissions and an extra column for CDR generation. The case of basalt-based EW-CDR in the Philippines is considered. The model allows the estimation of economic “ripple effects” (i.e., changes in the output levels of economic sectors) resulting from CDR deployment. The rest of this paper is organized as follows. Section 2 gives the formal problem statement. Section 3 describes the EEIO model formulation. Section 4 applies the model to the case of the Philippines. Finally, Section 5 gives the conclusions and discusses future research directions.

2. Problem statement

The formal problem is as follows. Given:

- Given the state of technology in an economy which quantifies the input and output flows of resources and wastes defined by an environmentally–extended input-output (EEIO) system,
- Given the resource requirements and waste streams of a new economic sector meant for carbon dioxide removal (CDR);
- Given the baseline economic and environmental performance of an economy;
- Given the target CDR removal;

The objective is to determine the economic effects of the large–scale implementation of CDR.

A generic economic system with environmental extension is illustrated in Figure 1.

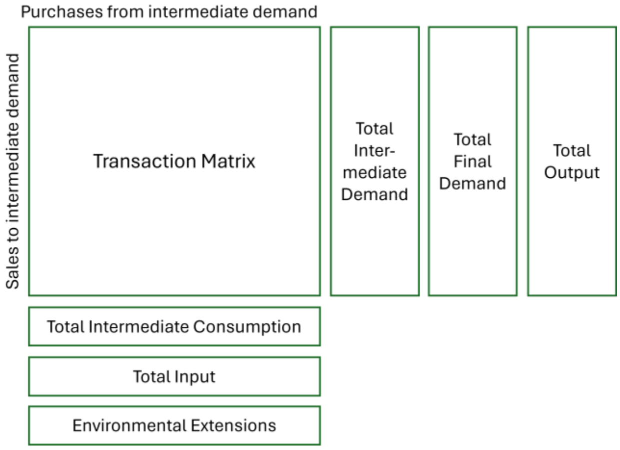

Figure 1: Input-output system with environmental extension

3. Input-output model formulation

The input-output model was developed by Leontief (1936) to represent the network structure of an economy using a system of linear equations. Detailed tutorials on the basic model, as well as extensions and variants, can be found in the book of Miller and Blair (2009). The basic input-output model is given in Eq(2). Where $\vec{y}$ is the final demand vector, $\vec{x}$ is the total output vector, $\vec{A}$ is the technology coefficient matrix, and $\vec{I}$ is an identity matrix.

$$\vec{y} = (\vec{I} - \vec{A})\vec{x} \tag{2}$$

This model can be solved by direct matrix inversion as shown in Eq(3):

$$\vec{x} = (\vec{I} - \vec{A})^{-1}\vec{y} \tag{3}$$

The EEIO model was then proposed by Leontief (1970) to consider the effect of pollutants and the introduction of a new sector for environmental clean-up (Eq(4)), where $\vec{b}^T$ is the CO_2 emissions satellite vector, $\vec{c}$ is the CDR cost vector, s is the CDR scale factor, z is the baseline CO_2 emission of the system, and δ is the CO_2 reduction.

$$\begin{pmatrix} (\vec{I} - \vec{A}) & \vec{c} \\ \vec{b}^T & -1 \end{pmatrix} \begin{pmatrix} \vec{x} \\ s \end{pmatrix} = \begin{pmatrix} \vec{y} \\ z - \delta \end{pmatrix} \tag{4}$$

Note that the EEIO model requires an additional row for direct sectoral CO_2 emissions, and an additional column for a new sector to produce CDR. The “final demand” of the additional row represents the residual CO_2 emissions that society is willing to tolerate after the application of CDR (Leontief, 1970). The extended model can still be solved by matrix inversion (Eq(5)):

$$\begin{pmatrix} (\vec{I} - \vec{A}) & \vec{c} \\ \vec{b}^T & -1 \end{pmatrix}^{-1} \begin{pmatrix} \vec{y} \\ z - \delta \end{pmatrix} = \begin{pmatrix} \vec{x} \\ s \end{pmatrix} \tag{5}$$

The required calculations can be implemented in different computing environments such as Microsoft Excel.

4. Philippine case study

This section describes the development of an EEIO model for assessing the effects of basalt-based EW in the Philippines. Data from 2018 is used since this is the most recent available. Due to space constraints, the official input-output data (Philippine Statistics Authority, 2024) is compressed into an 8-sector model. Sectoral CO_2 emissions data from fuel combustion (Philippine Department of Energy, 2024) are used together with the input-output data to estimate the CO_2 intensities. Techno-economic data for the EW-CDR sector are based on Rinder and von Hagke (2021) combined with assumptions as stated below. The resulting model is used to determine changes in sector total outputs at fixed GDP for 5–20 % reduction in CO_2 emissions.

Table 1 shows the dimensionless technical coefficients of the input-output model. Each column gives the average monetary value of purchased inputs needed to produce one unit of output of a sector, measured in monetary terms. In practice, these coefficients represent the performance of the average production technology used by each sector. Table 2 gives the monetary total output and final demand levels of the economic sectors. Total outputs are larger than the respective final demands because they include intermediate goods that are used as production inputs in other sectors. Note that physical quantities implied by these monetary values can easily be found if the average prices are known (Leontief, 1936).

Table 3 gives the direct CO_2 emissions intensities of the economic sectors in Mt CO_2/billion PHP (or t CO_2/thousand PHP, where EUR1 = PHP60). The values are derived from the absolute emissions inventories (Philippine Department of Energy, 2024) and the corresponding total outputs in Table 2. The actual emissions from the sectors are directly proportional to the level of output, assuming that the average technology mix represented by these factors remains constant.

Table 4 gives the techno-economic coefficients of the new EW-CDR sector, which involves mining, comminution, transport, and application of silicate rocks; this constitutes $\vec{c}$ in Eq(4). These coefficients are the values of major purchased inputs in billion PHP/Mt CO_2 (or thousand PHP/t CO_2). The physical factors assumed here are based on Rinder and von Hagke (2021). The coefficient for Mining (S2) is the cost of purchase of basalt, assuming a price of PHP555/t and a CDR factor of 0.3 t CO_2/t. The coefficient for Manufacturing (S3) is the cost of purchase of supplies for direct EW-CDR operations; the cost of diesel fuel for the tractors used to apply basalt powder is taken as a proxy for all non-capital inputs, assuming an average price of PHP47/L. The coefficient for Electricity (S4) is based on a power demand of 180 kWh/t to grind the basalt to the required particle size (~10 μm), assuming an average price of PHP8.99/kWh. Finally, the coefficient for Transportation (S7) represents the cost of the service to move basalt by truck an average distance of 150 km from the grinding plants to the application sites. For all of these inputs, it is assumed that the marginal mix of technologies needed to meet the incremental intermediate demands of the EW-CDR sector is the same as the background technology mix. This assumption of fixed "recipes" is consistent with the properties of Leontief production functions (Leontief, 1936).

Table 1: Matrix of dimensionless technical coefficients (adapted from Philippine Statistics Authority, 2024)

Sector	S1	S2	S3	S4	S5	S6	S7	S8
Agriculture (S1)	0.288	0.004	0.122	0.002	0.001	0.003	0.000	0.002
Mining (S2)	0.000	0.098	0.035	0.028	0.010	0.000	0.000	0.000
Manufacturing (S3)	0.162	0.134	0.323	0.189	0.394	0.034	0.243	0.067
Electricity (S4)	0.007	0.017	0.023	0.043	0.014	0.015	0.017	0.016
Construction (S5)	0.000	0.001	0.000	0.000	0.000	0.001	0.001	0.002
Trade (S6)	0.011	0.022	0.099	0.041	0.059	0.135	0.029	0.050
Transportation (S7)	0.005	0.014	0.018	0.003	0.006	0.025	0.158	0.010
Other services (S8)	0.018	0.044	0.060	0.073	0.059	0.093	0.151	0.250

Table 2: Baseline sectoral total outputs and final demands (adapted from Philippine Statistics Authority, 2024)

Sector	Total output (billion PHP/y)	Final demand (billion PHP/y)
Agriculture (S1)	3,461	1,090
Mining (S2)	245	–223
Manufacturing (S3)	10,939	4,094
Electricity (S4)	897	260
Construction (S5)	3,008	2,969
Trade (S6)	4,668	2,066
Transportation (S7)	1,737	990
Other services (S8)	11,584	7,019

Table 3: Direct sectoral CO_2 intensities (adapted from Philippine Department of Energy 2024)

Sector	Direct CO_2 intensity ($Mt\ CO_2$/billion PHP)
Agriculture (S1)	0.0005
Mining (S2)	0.0010
Manufacturing (S3)	0.0010
Electricity (S4)	0.0720
Construction (S5)	0.0010
Trade (S6)	0.0005
Transportation (S7)	0.0119
Other services (S8)	0.0005

Table 4: Techno-economic coefficients of EW-CDR sector (adapted from Rinder and von Hagke, 2021)

Sector	Input (billion PHP/Mt CDR)
Mining (S2)	1.85
Manufacturing (S3)	0.23
Electricity (S4)	5.4
Transportation (S7)	2.8

The model is used to estimate the effect of reducing the baseline emissions of 109.3 Mt CO_2/y by 5–20 %. Achieving these decarbonization scenarios requires the generation of 10.4–41.7 Mt/y of CDR to reduce emissions to 87.5–103.9 Mt CO_2/y. This scale of EW-CDR requires the application of 34.7–138.9 Mt/y of basalt on a total land area of 0.23–2.78 Mha, based on an application rate of 50–150 t/ha/y (Strefler et al., 2018). Due to interdependencies among economic sectors, the introduction of EW-CDR increases the demand for other goods that are directly or indirectly linked to this new sector. Figure 1 shows the percentage increase in outputs of the economic sectors as a result of introducing EW-CDR. Note that the direct CO_2 emissions of these sectors also increase by the same proportions. The largest relative increases occur in Mining (S2), Electricity (S4) and Transportation (S7). Figure 2 shows the absolute values of the direct CO_2 emissions of the sectors under the same scenarios. The largest increase occurs in emissions from Electricity (S4) due to the energy requirement for grinding basalt.

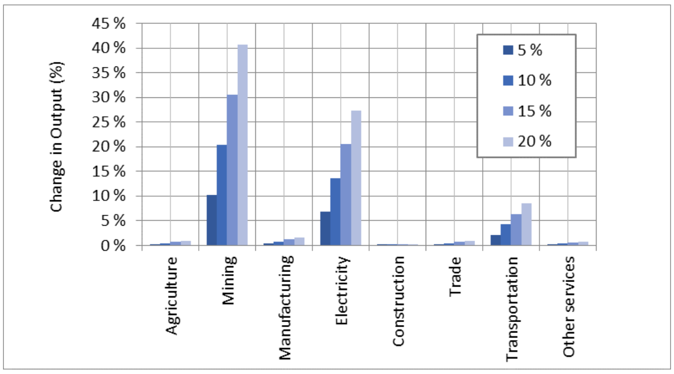

Figure 1: Percentage increase in sector total outputs for 5–20 % decarbonization scenarios

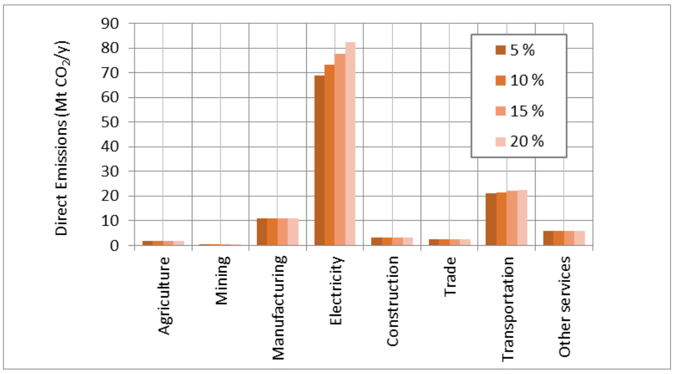

Figure 2: Direct sectoral emissions for 5–20 % decarbonization scenarios

5. Conclusions

In this work, an EEIO model was developed to estimate the amount of basalt-based EW-CDR needed to reduce the CO_2 emissions of the Philippine economy by 0–20 % from baseline. By considering interdependencies within the economic system, including the intermediate inputs drawn by the EW-CDR sector from the rest of the economy, the model can estimate the ripple effects of the large-scale use of this decarbonization strategy. Under the assumptions consistent with Leontief production functions, an estimated 41.7 Mt/y of EW-CDR is needed to reduce the total CO_2 emissions by 20 %, from 109.3 to 87.5 Mt/y. In future work, the modelling approach used here can be readily applied to other geographic contexts. It can also be extended to other NETs, such as DAC, provided the necessary techno-economic data is available. Mathematical programming variants can also be developed for optimizing the mix of NETs when multiple options are simultaneously considered.

Nomenclature

$\vec{A}$ – Technical coefficient matrix
$\vec{b}$ – CO_2 emissions satellite vector
$\vec{c}$ – CDR cost vector
$\vec{I}$ – Identity matrix
$\vec{y}$ – final demand vector
z – baseline CO_2 emissions

δ – target CO_2 reduction

Decision variables
s – CDR scale factor
$\vec{x}$ – total output vector

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