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A linear program for optimizing enhanced weathering networks

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A R T I C L E I N F O

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A B S T R A C T

We develop a linear programming (LP) model for optimizing enhanced weathering (EW) networks. EW is a negative emissions technology (NET) that involves mining and grinding of naturally occurring CO_2-reactive rocks, and subsequently applying the resulting powder to soil to provide ample surface area for contact with the atmosphere and thus accelerate carbon fixation. Use of EW as a carbon management strategy at scale will result in the need to properly match sources (rock crushing plants) with sinks (application sites); the result is a special case of a supply chain optimization problem. The model proposed here can determine optimal matches of sources and sinks in EW-based CMNs, considering material flow and temporal constraints. A case study is solved to illustrate the model.

Introduction

Climate change is now widely regarded as the single most critical environmental issue facing the world today. As greenhouse gas (GHG) emissions continue to grow in response to economic and demographic trends, it has been argued that negative emissions technologies (NET), also known as carbon dioxide removal (CDR) techniques, will need to be deployed at commercial scales in the near future in order to stabilize climate [1]. Among existing NET options is enhanced weathering (EW), which relies on the acceleration of the slow natural weathering of rocks to fix atmospheric CO_2 [2]. In terrestrial EW-based systems, these CO_2-reactive rocks (e.g., those containing silicates) are mined, crushed into a powder, and then applied to soil to increase surface area of contact and thus accelerate the weathering process. In the presence of moisture from precipitation, CO_2 is fixed from the air, and the final reaction products in the form of water-soluble bicarbonates are gradually washed out by run-off into the sea. The cost and GHG abatement potential of EW depends on factors such as energy consumption for quarrying operations, rock crushing, transportation and logistics, and application to soil [3,4]. The theoretical potential of EW to generate negative emissions is large; for example, Renforth [4] estimates that the silicate resources in the United Kingdom have the potential to sequester 430 Gt of CO_2, based on a stoichiometric capture potential of 0.3 t CO_2 t^{-1} rock; the presence of large reserves of such mineral resources suggests that the sequestration potential of EW-based systems will be determined by factors such as mining, crushing, and transportation capacity, as well as the availability of agricultural land under appropriate weather conditions to be used as application sites. In practice, future EW-based systems will operate as supply chains that make use of existing transportation networks used for shipment of agricultural produce [5].

Future large scale implementation of EW as a NET will require matching of sources (rock crushing plants) and sinks (application sites) in order to maximize CO_2 sequestration. Such systems can be regarded as a special class of carbon management networks (CMNs) [6], which can be optimized using supply chain models. To date, no record exists in the scientific literature on the development of supply chain optimization models for EW.[1] Nevertheless, such models will be needed in the future if EW is to be utilized on a large scale to help mitigate global CO_2 emissions. This paper addresses this research gap by developing a novel linear programming (LP) model for optimizing future EW-based CMNs. This model is adapted from a generic model for optimizing CMNs [7]. The model formulation is given in the next section; an illustrative case study is then solved to demonstrate the model. Finally, conclusions and prospects for future work are discussed.

Formal problem statement

The model requires the following inputs:

- A set of sources (rock crushing plants), each with a predefined annual output capacity and operating life;

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[1] As of May 31, 2019, searching the Scopus database using "enhanced weathering" and "supply chain" as keywords yielded zero documents.

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Table 1
Limiting data for sources and sinks in case study.

Sources (i)	Rock quantity in kt	Rock flowrate in kt/y (S_i)	Operating life in y (P_i)	Sinks (j)	Rock quantity limit in kt (C_j)	Rock flowrate in limit in kt/y (D_j)	Operating life at maximum application rate in y
1	25	1.00	25	1	4	0.40	10
2	40	2.00	20	2	16	0.80	20
3	75	2.50	30	3	20	1.00	20
				4	15	0.60	25
				5	160	4.00	40

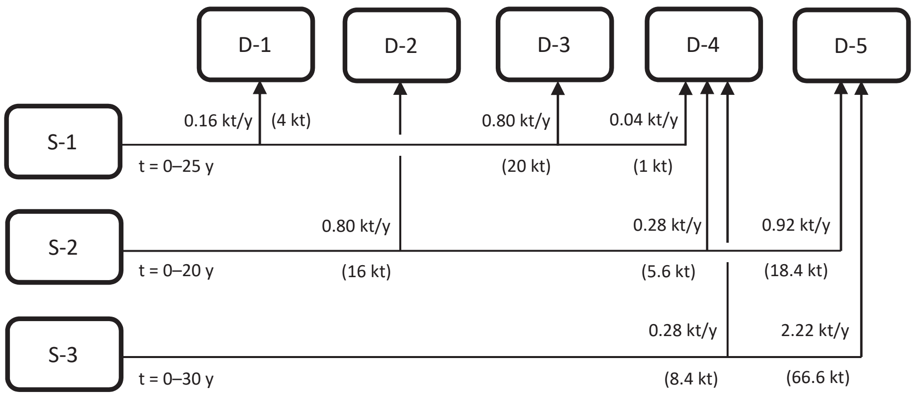

Fig. 1. Optimal matching of sources and sinks in case study.

- A set of sinks (application sites), each with a predefined limit to annual crushed rock application rate, as well as a final limit to cumulative application;
- A predefined CO_2 sequestration potential per unit of crushed rock;
- A predefined average carbon footprint for rock quarrying, transport and crushing;

It is assumed that all components of the EW network begin to operate at the same time, but their economic lives need not coincide. Variations in the rock carbon footprint are assumed to be negligible compared to the CO_2 specific sequestration potential. The optimization model then determines the largest possible total negative emissions for the system, and the matching of the sources and sinks that achieves this optimum.

Model formulation

The LP model is formulated as follows:
Minimize

$$\Sigma_i \Sigma_j (\alpha + \beta_{ij}) P_i r_{ij} \tag{1}$$

Subject to:

$$\Sigma_j r_{ij} \leq S_i \ \forall i \tag{2}$$

$$\Sigma_i r_{ij} \leq D_j \ \forall j \tag{3}$$

$$\Sigma_i P_i r_{ij} \leq C_j \ \forall j \tag{4}$$

$$r_{ij} \geq 0 \ \forall j \tag{5}$$

where α is the CO_2 removal per unit of crushed rock applied, β_{ij} is the CO_2 footprint per unit of crushed rock (including emissions from quarrying, transportation and crushing) allocated from source i to sink j, P_i is the operating life of operation of source i, r_{ij} is the annual flowrate of crushed rock from source i to sink j, S_i is the maximum annual production rate of source i, D_j is the maximum annual application rate at sink j, and C_j is the maximum cumulative amount of crushed rock that can be applied to sink j. The magnitudes of the latter three model parameters are exogenously determined by the capacities of the rock crushing plants, as well as the land area, soil characteristics, and weather conditions at the application sites.

The objective function (1) seeks to minimize CO_2 emissions. In general, parameter α has a negative value and is larger in magnitude than β. Constraints (2) and (3) give the production and application limits, respectively. In (3), the limit to the annual rate of application of crushed rock is dependent on meteorological and hydrological conditions which determine the rate of CO_2 fixation. Constraint (4) specifies the ultimate limit to crushed rock application over the life of the system; in practice, this will be based on any adverse effects of mineral residue deposition at the application site. Temporal aspects of the model result from the interplay of annual and total flows described by constraints (3) and (4). All variables in the model are non-negative (5).

Illustrative example

A small illustrative example with three sources and five sinks is solved here to illustrate the model capabilities. The model is implemented in the optimization software LINGO 13.0, and solved with negligible time using a laptop with 8.00 GB RAM, i7-3540MCPU and a 64-bit operating system running on Windows 8 Pro. Characteristics of the sources and sinks are given in Table 1; these values are hypothetical values but are representative of typical capacities in future EW systems. The value of α is -0.3 kt CO_2/t, while all parameters β_{ij} are assumed to have the same value of 0.05 kt CO_2/t.

The matching of sources and sinks can then be determined by solving the model using these inputs. The resulting optimal EW-based CMN is given in Fig. 1. Annual flowrates are shown in kt/y, while cumulative amounts of rock applied are given in kt in parentheses. All streams in this network exist for the entire operating lives of the sources as indicated; no redistribution occurs during the operations. This network results in net cumulative emissions amounting to -35 kt over the entire time horizon of operations. The model can be easily scaled up to optimize larger systems, provided that similar data are available for the sources and sinks. The LP can also be implemented and solved in other software environments, including spreadsheet applications such as Excel.

Conclusions

An LP model has been developed for optimizing EW-based CMNs. The model maximizes carbon sequestration based on physical and temporal characteristics of sources (rock crushing plants) and sinks (application sites) in the network. Its capability has been demonstrated using an illustrative case study. This simple model can act as the core to which additional features can be added for the development of future models. Such enhancements can account for more detailed operational issues, such as sequestration cost, risk level, data uncertainties, and other relevant aspects.

Declaration of conflict of interest

The authors declare no conflict of interest.

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