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Pinch-based planning of terrestrial carbon management networks

Raymond R. Tan [a,*], Kathleen B. Aviso [a], Santanu Bandyopadhyay [b]

[a] Chemical Engineering Department, De La Salle University, 2401 Taft Avenue, 0922, Manila, Philippines
[b] Department of Energy Science and Engineering, Indian Institute of Technology Bombay, Powai, Mumbai, 400076, India

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ABSTRACT

Negative emissions technologies (NETs) will be needed to achieve deep cuts in greenhouse gas emissions and mitigate climate change in the coming decades. Enhanced weathering and biochar application are two NETs that are based on the enhancement of naturally occurring processes; compared to other NETs, they have the advantage of relying on mature component technologies. Both technologies offer the prospect of sequestering carbon from the atmosphere at the scale of multiple gigatons per year if deployed commercially via carbon management networks (CMNs). However, planning future CMNs will present similar challenges as optimizing supply chains for current product systems. In this work, a pinch analysis approach for the planning of CMNs based on either enhanced weathering or biochar application is developed. Planning is framed as a source-sink problem typical in process integration (PI) applications, allowing pinch analysis to be applied to determine optimal system targets and synthesize the corresponding CMNs. General principles of pinch analysis are shown to be applicable to the planning problem. Case studies on enhanced weathering and biochar application CMNs are solved to illustrate this approach.

1. Introduction

Drastic climate change mitigation measures have to be adopted on a global scale to limit the average temperature rise to well below 2 °C by 2100 (Intergovernmental Panel on Climate Change et al., 2018). This target requires total greenhouse gas (GHG) emissions to be reduced to a net-zero level by mid-century; such deep cuts can only be achieved through concerted use of available carbon management strategies that include negative emissions technologies (NETs) (Haszeldine et al., 2018). NETs deliver carbon dioxide removal (CDR) through different chemical, biological, or physical pathways for drawing down carbon from atmospheric CO_2 and then transferring it to different compartments for final storage. Examples of these technologies are bioenergy with CO_2 capture and storage (BECCS), direct air capture (DAC), afforestation/reforestation, soil carbon management, enhanced weathering, and biochar application. The research landscape of NETs was recently reviewed by Minx et al. (2018). Two companion review papers also gave surveys of their CDR potential along with risks associated (Fuss et al., 2018) and commercialization outlook (Nemet et al., 2018). The implications of NET deployment on the Sustainable Development Goals (SDGs) were assessed in a recent paper by Smith et al. (2019). Due to the severity of the climate issue, Fajardy et al. (2019) argued for an urgent need for a global research agenda and policy framework for NETs.

Large-scale deployment of NETs as a carbon management strategy will incur a significant cost as well as land, water, and nutrients footprints. Some NETs, such as DAC and enhanced weathering, also require energy inputs, although others such as BECCS and biochar application provide positive net energy output (Thengane and Bandyopadhyay, 2020). Footprint constraints thus need to be considered in planning NET use. Smith et al. (2016a) estimated the footprint-constrained global potential of key NETs to be in the order of multiple gigatons per year. They also discussed the tradeoffs involved in the selection of NET options. Similar studies have been reported at the scale of individual countries, such as Scotland (Alcalde et al., 2018), Ireland (McGeever et al., 2019), and the entire United Kingdom (Smith et al., 2016b). In the case of countries with a low per capita carbon footprint and low population density, NET deployment can be sufficient to approach net-zero emission levels (Alcalde et al., 2018). However, systematic decision support tools are needed to maximize the benefits of NETs, given the prevailing footprint constraints. Tan et al. (2020) proposed using process integration (PI) approaches to optimize the deployment of NETs as a carbon management strategy.

PI is a branch of engineering that deals with the optimal use of limited resources. The earliest application of PI was heat recovery and

* Corresponding author.
E-mail address: raymond.tan@dlsu.edu.ph (R.R. Tan).

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energy conservation in process plants (Linnhoff et al., 1982). However, PI principles have been extended to economizing the use of other industrial resources. The diversification of PI applications is well-documented in a handbook of major contributions (Klemeš, 2013) and a comprehensive review article (Klemeš et al., 2018); previously conflicting PI schools of thought based pinch analysis and mathematical programming have also developed increased synergy (Klemeš and Kravanja, 2013). The application of PI to carbon-constrained planning problems was first proposed by Tan and Foo (2007). This sub-area has broadened to the optimization of various carbon management networks (CMNs) (Tan and Foo, 2018), with crucial developments being documented in a recent monograph (Foo and Tan, 2020). Pinch analysis has been used for classes of CMNs that are relevant to NET deployment. For example, methods for the design of CO_2 allocation networks with concurrent (Tan et al., 2012) and non-concurrent (Diamante et al., 2014) sources and sinks are applicable to planning BECCS and DAC systems. An approach to integrate multiple CO_2 utilization processes was also developed (Thengane et al., 2019). Tan et al. (2018) developed a graphical approach for planning CMNs based on biochar application; this work considered the risk of soil contamination as a constraint on the CDR that can be reached. Alternatively, PI-based mathematical programming models have been developed for terrestrial NETs, such as enhanced weathering (Tan and Aviso, 2019) and biochar application (Tan, 2016). However, there is still a clear research gap in the literature on pinch analysis for planning these terrestrial NETs. No papers have been published to date that addresses terrestrial NETs in a unified manner based on their common problem structures.

To address this research gap, this paper develops a unified pinch analysis approach to planning CMNs based on enhanced weathering or biochar application. The deployment pathways of these two terrestrial NETs are structurally similar, and can be framed as a source-sink matching problem that is analogous to many PI problems. The pinch analysis approach allows the identification of the optimal system target prior to detailed design; it also facilitates problem decomposition and analysis, so as to allow generation of alternative CMNs that achieve the target. The pinch-based approach allows engineering insights to be applied systematically towards planning terrestrial CMNs. The rest of this article is organized as follows. Section 2 provides a brief review of the literature on enhanced weathering and biochar application. Section 3 presents the formal problem statement addressed in this work. Section 4 describes the graphical pinch analysis methodology. Sections 5 and 6 illustrate the methodology on enhanced weathering and biochar application case studies. Finally, Section 7 gives the conclusions and prospects for future research.

2. Literature review on terrestrial NETs

This section gives a brief review of the literature on enhanced weathering and biochar application as terrestrial NETs. Both of these technologies involve the addition of crushed material to the soil at the application sites – i.e., powdered alkaline minerals in the case of enhanced weathering, and carbonized biomass in the case of biochar application. As a result, the planning of these terrestrial CMNs involves matching sources (mineral crushing or biomass pyrolysis plants) and sinks (marginal or agricultural land at the application sites). The structural analogues are evident in the previous PI models developed for enhanced weathering (Tan and Aviso, 2019) and biochar application (Tan, 2016). Although both are rated as intermediate in terms of system-level technological maturity (McLaren, 2012), all of the component processes in enhanced weathering and biochar application are individually technologically and commercially established. While unproven for large-scale carbon drawdown, the application of powdered minerals and biochar on agricultural land is already practiced commercially to improve soil quality. This relative maturity is an important advantage of terrestrial NETs over competing alternatives such as BECCS and DAC. A potential co-benefit from their use is that the improvement of soil quality results in the reduction of carbon, nitrogen, and phosphorus footprints from synthetic fertilizer application and thereby indirect reduction of CO_2 emissions. However, particulate matter emissions from these applications are a potential adverse side effect and limits the overall carbon capture (Renforth, 2012). However, despite the structural similarities at the CMN level, the carbon sequestration mechanisms of enhanced weathering and biochar application are very different.

As the term suggests, enhanced weathering relies on the acceleration of naturally occurring weathering reactions of rocks and minerals with CO_2 and water. In the case of silicate minerals, these reactions yield residual silica and dissolved bicarbonate ions as final products; the ions are then carried into final storage in the oceans by runoff water. In a well-designed enhanced weathering system, none of the sequestered carbon is stored at the application site. The potential to sequester CO_2 through enhanced weathering was first proposed by Seifritz (1990). Its viability was then demonstrated in laboratory experiments (Kojima et al., 1997). Both natural (e.g., basalt) and synthetic (e.g., metallurgical slag) silicate-based materials can be used in enhanced weathering. The material needs to be mechanically reduced into a powder with particle size in the order of 10 μm to increase surface area and accelerate the weathering to a rate that is suitable for carbon management applications (Renforth, 2012). A cost-benefit analysis should consider the energy requirement (and GHG emissions) of particle size reduction, and the rate of feasible application depends on weather conditions (i.e., temperature and precipitation) at the site (Strefler et al., 2018). The CDR potential of enhanced weathering on cropland in Brazil, China, India, and the USA was recently estimated at 0.5–2 Gt/y CO_2 at a cost of US$ 80–180/t CO_2 (Beerling et al., 2020); additional capacity is clearly possible by also using marginal lands as application sites.

Enhanced weathering can have favorable or adverse impacts other than the resulting CDR. Edwards et al. (2017) argued that it could improve soil quality and reduce the need for irrigation and synthetic fertilizer. Smith et al. (2019) noted that these agricultural benefits could have positive impacts on SDGs. Lefebvre et al. (2019) performed life cycle analysis (LCA) of enhanced weathering using basalt in Brazil, and noted the strong influence of transportation in determining net benefits. Cox and Edwards (2019) proposed financing mechanisms to enable farmers to use enhanced weathering; they also argued that this NET is most effective when using rock residues rather than freshly quarried material. There is also significant potential in the use of industrial waste such as mine tailings (Power et al., 2020) or slag (Pullin et al., 2019) for enhanced weathering. The theoretical global CDR potential of industrial waste is estimated to reach up to 8.5 Gt/y CO_2 by 2100 (Renforth, 2019). However, the actual extent of use of enhanced weathering will be limited primarily by land footprint and energy supply constraints (Smith et al., 2016).

Unlike enhanced weathering, the negative emissions of biochar application to soil result mainly from the long-term terrestrial storage of chemically stable carbon in pyrolyzed biomass (Woolf et al., 2010). Compared to raw biomass, biochar sequesters carbon for the multi-century time scales required for effective climate change mitigation (Lehmann, 2007). Alternative thermochemical processes such as torrefaction can also be used (Thengane et al., 2020). Since the carbon content of biomass is fixed via photosynthesis from the air, biochar application gives a net transfer of carbon from the atmosphere to the terrestrial compartment. Biochar application is related to soil carbon sequestration, except that the carbon is stored in chemically recalcitrant form; it can provide similar benefits in soil quality and agricultural productivity (Smith, 2016). The CDR potential of biochar application was estimated at up to 6.6 Gt/y of CO_2 by Woolf et al. (2010). Roberts et al. (2010) used LCA to analyze the GHG, energy, and economic aspects of biochar application on cropland as a NET. Their results showed significant potential for secondary reductions in GHG emissions due to the co-production of renewable fuel (i.e., biogas and bio-oil) and improvement in soil conditions. A recent review of LCAs of biochar

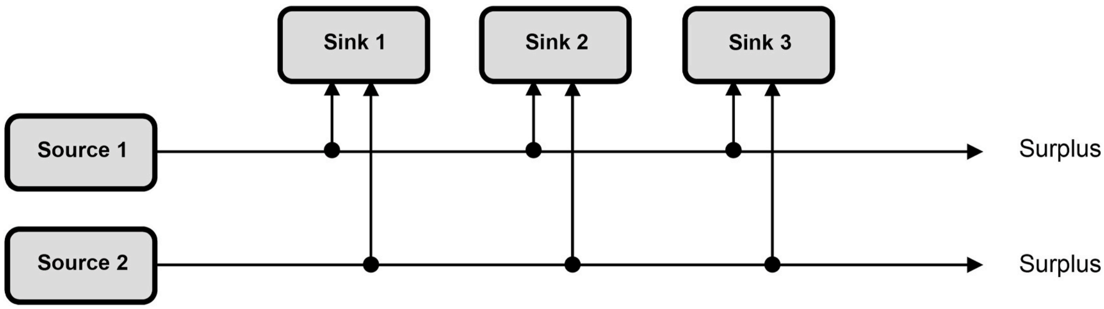

Fig. 1. Superstructure for source-sink matching in terrestrial CMN optimization.

application schemes confirms these initial findings (Matuštík et al., 2020). In practice, the application of biochar at a given site will be limited by local soil conditions and the level of undesirable contaminants in the biochar itself (Tan, 2016).

As with enhanced weathering, there may be potential risks and co-benefits that result from applying biochar to soil. The main risk is the accumulation of impurities (e.g., salts, dioxins) in soil, while the main benefits result from improved fertility and water retention. Co-production of biogas and bio-oil also gives the potential to displace fossil energy. Smith et al. (2019) estimated that biochar application could give similar SDG benefits as enhanced weathering due to these improvements in agricultural productivity. Belmonte et al. (2017)

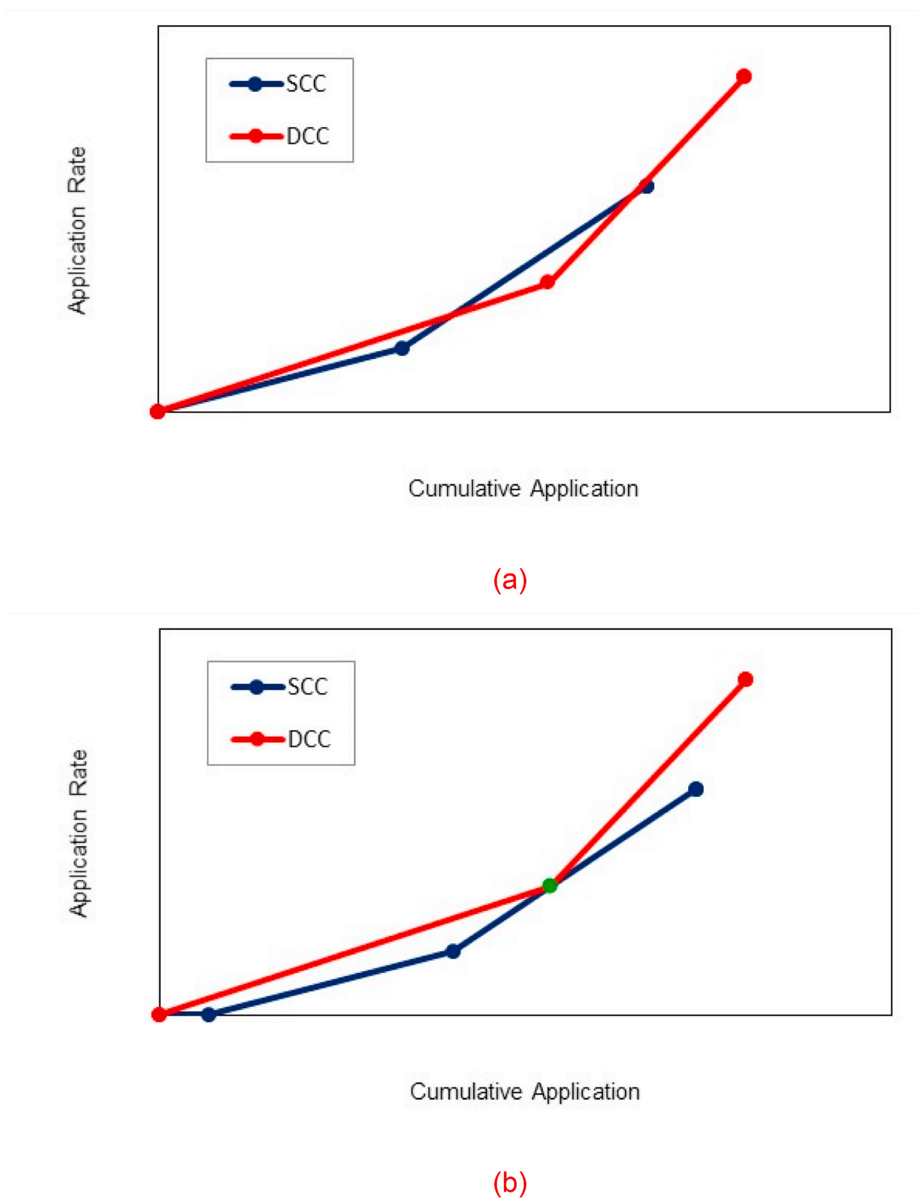

Fig. 2. Composite curves in (a) infeasible and (b) optimal orientation.

argued that process systems engineering (PSE) tools could play a vital role in optimizing the use of biochar within the food-energy-water nexus. Fan et al. (2020) analyzed the tradeoff between the use of biomass as a source of renewable energy and as a feedstock for biochar production, and identified criteria for determining which pathway offers more climatic benefit. Fan et al. (2021) recently examined the environmental and techno-economic aspects of biochar application as a NET. Ong et al. (2021) developed an optimization model integrating biochar in agro-industrial value chains. Schmidt et al. (2019) proposed a framework for pyrolytic carbon capture and storage (PyCCS) that supplements terrestrial biochar application with additional sequestration pathways, such as geological storage or use of pyrolysis byproducts for non-combustion applications. Tan (2019) discussed the need for data acquisition and monitoring systems to verify the CDR benefits of biochar application (it should be noted that the same verification issues also occur for enhanced weathering).

System-level implementation of both enhanced weathering and biochar application can be framed as a source-sink matching problem, which is structurally similar to many PI problems that are solved via pinch analysis. The pinch-based approach to planning these terrestrial CMNs is developed in the succeeding sections.

3. Problem statement

The formal problem statement for terrestrial CMNs is as follows:

- Given *m* sources (i.e., mineral crushing or pyrolysis plants) with known annual production capacity and operating life;
- Given *n* application sites with known annual and cumulative application rate limits; and
- Given CO_2 sequestration factors per unit of crushed mineral or biochar applied.

It is assumed that all sources and sinks in the system commence operation at the same time. Application limits at the storage sites are also assumed to consider the relevant technical, environmental, and socio-economic constraints (Renforth, 2012). The problem is to determine the optimal target (maximum CDR) for the system, and then to synthesize the CMN that achieves this target. Alternative optimal network topologies should also be identified if these exist. The superstructure may be visualized for the case of a system with two sources and three sinks as shown in Fig. 1.

4. Methodology

The graphical pinch methodology in this work is based on an approach previously developed for optimizing resource allocation networks. The latter targeting approach was developed independently by Prakash and Shenoy (2005), who noted its equivalent linear programming (LP) formulation, and El-Halwagi et al. (2003), who established proof of optimality via dynamic programming. The nearest neighbor algorithm (NNA) was also proposed by Prakash and Shenoy (2005) for network synthesis, and a subsequent paper developed a procedure for network evolution (Das et al., 2009). This graphical approach was adapted for carbon emissions pinch analysis (CEPA) by Tan and Foo (2007), and for CO_2 network synthesis in CCS systems by Tan et al. (2012). However, it should be noted that this approach is only one of multiple graphical or algebraic pinch analysis methods that are mathematically equivalent (Bandyopadhyay, 2015); it can also be extended to handle non-deterministic data (Bandyopadhyay, 2020).

The mains steps of the methodology are as follows:

S1. Tabulate the cumulative output and annual capacity of the sources in order of descending operating life. Note that the cumulative output of each source can be found by multiplying its annual capacity by its operating life.

S2. Tabulate the cumulative and annual application rate limits of the sinks in order of descending minimum operating life. Note that the operating life of each sink is variable, but a lower bound can be determined. The latter can be found by dividing a sink's cumulative application limit by its annual application rate limit; this minimum operating life gives the shortest feasible period that a sink's capacity can be saturated without exceeding the maximum allowable annual application rate.

S3. Generate the source composite curve (SCC) by plotting each source from S1 sequentially on rectangular coordinates, with cumulative output as the horizontal axis and annual capacity as the vertical axis. Note that the slope of each segment of the SCC is the reciprocal of the source operating life.

S4. Generate the demand composite curve (DCC) by plotting each sink from S2 sequentially on the same rectangular coordinates as the SCC. The slope of each segment of the DCC is also the reciprocal of the sink minimum operating life.

S5. Inspect the initial relative orientation of the SCC and DCC. If the SCC is entirely on the right side of the DCC, then the initial solution is already feasible and optimal. If this geometric condition is not met as shown in Fig. 2a, translate the SCC horizontally to the right until the optimality condition is satisfied. The result is shown in Fig. 2b. This minimum distance of horizontal translation gives the system's optimal target; it results in at least one point where the SCC and DCC are tangent to each other as shown by the green point in Fig. 2b. The point/s of tangency is/are the pinch point/s. The significance of the pinch is revisited in a later step.

S6. Inspect the pinch diagram and identify the horizontal span of overlap of the SCC and DCC. This horizontal distance gives the optimal cumulative application (of crushed mineral or biochar) that is possible for the system, given the specified characteristics of the sources and the sinks. The optimal amount of cumulative CDR can be deduced by multiplying this result with the stoichiometric factor that is applicable to either enhanced weathering or biochar application.

S7. If a single pinch point is identified in S5, it divides the system into two regions; the first occurs below and to the left of the pinch point, while the second occurs above it and to its right. Because of the pinch point, the problem is decomposed into two subproblems that can be solved independently of each other; as a consequence of the golden rule of pinch analysis, cross-pinch transfer of material is not possible (except for the source that forms the pinch point with the DCC). The below-pinch region will have surplus cumulative application capacity that is indicated by the horizontal translation distance used in S5. Depending on the horizontal spans of the SCC and DCC, the above-pinch region may have a surplus or deficit in application capacity. Any deficit means that some of the material output from the sources cannot be accommodated within the system.

S8. The optimal network for the system can be determined using a source-sink matching procedure such as NNA (Prakash and Shenoy, 2005); then, alternative optimal and near-optimal networks can also be generated using network evolution (Das et al., 2009).

This pinch analysis approach is only intended for preliminary, high-level planning for terrestrial carbon capture. PI-based mathematical programming is more suitable for detailed planning involving case-specific factors by adding user-defined constraints to the basic LP

Table 1
Source data for Case Study 1 (Tan and Aviso, 2019).

Source	Annual Capacity (kt/y)	Operating Life (y)	Cumulative Output (kt)
1	2.50	30	75
2	1.00	25	25
3	2.00	20	40

Table 2
Sink data for Case Study 1 (adapted from Tan and Aviso, 2019).

Sink	Annual Capacity (kt/y)	Cumulative Output (kt)	Minimum Operating Life (y)
1	2.50	100	40
2	0.60	15	25
3	1.11	20	18
4	1.00	15	15
5	0.50	5	10

formulation (Poplewski et al., 2010). The methodology is illustrated in the succeeding sections for both enhanced weathering and biochar applications.

5. Case study 1: enhanced weathering

This case study is adapted from the basalt rock enhanced weathering example of Tan and Aviso (2019). The data for the sources are given in Table 1, and are identical to the assumptions used in the original paper. The data for the sinks are given in Table 2 and have been modified. In practice, these application limits should consider adverse impacts such as particulate matter emissions and excessive changes in soil chemistry (Renforth, 2012). Both data sets are already arranged in the sequence required in steps S1 and S2. The CO_2 sequestration factor is assumed to be 0.3 kt CO_2/kt rock applied.

Implementing steps S3 and S4 to generate the superimposed SCC and DCC gives Fig. 3. It can be seen that this is an infeasible solution since the SCC is above the DCC. Next, applying S5 by translating the SCC by 25 kt results in the optimal solution indicated by the pinch diagram in Fig. 4. Note that an infinite number of pinch points occur along the entire length of the segment corresponding to Sink 2 (shown in green). It can also be seen that the horizontal span of overlap of the SCC and DCC is 130 kt, which gives the cumulative amount of crushed basalt that can be applied within the system. Using S6, the corresponding cumulative CDR is found to be 39 kt.

The significance of the pinch points can be shown using S7. Only Sink 1 lies below the pinch, and the 25 kt target represents the portion of its cumulative application limit that cannot be used. This result means that only 75% of sink capacity below the pinch can be utilized. There are an infinite number of pinch points because Sink 2 on the DCC coincides exactly with part of Source 2 on the SCC. Sinks 3–5 all lie above the

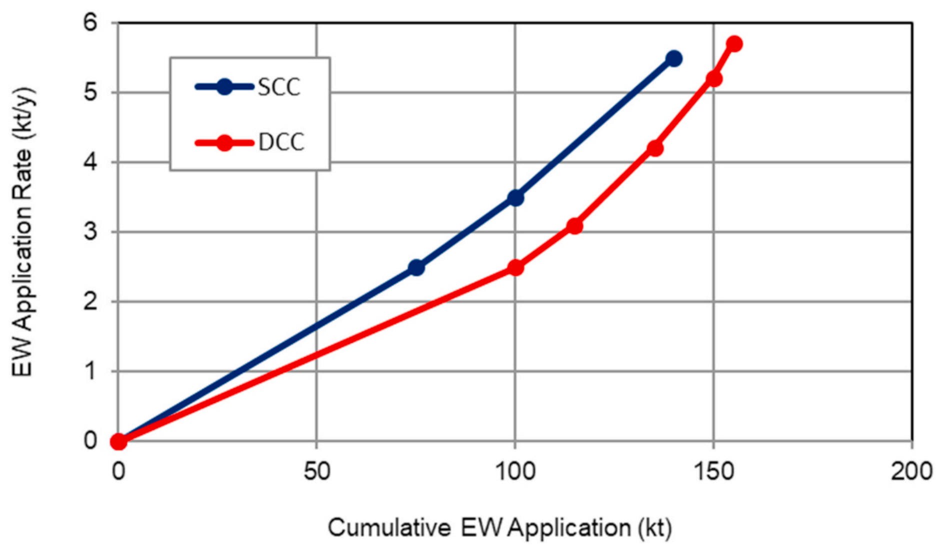

Fig. 3. Initial orientation of SCC and DCC for Case Study 1

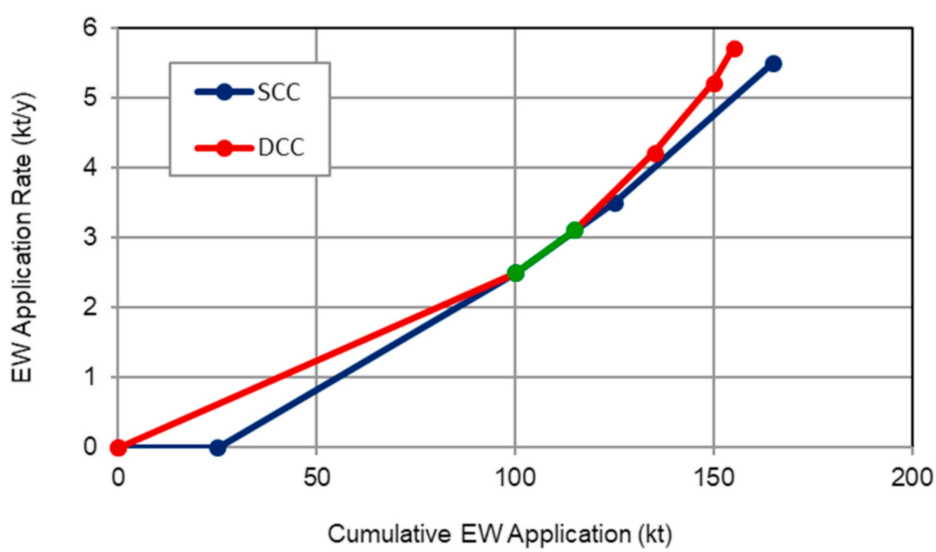

Fig. 4. Pinch diagram showing optimal solution for Case Study 1.

Table 3
Optimal CMN 1 for Case Study 1 showing basalt allocation (in kt).

Source	Sink					Surplus
	1	2	3	4	5	
1	75					
2		15	10			
3			10	15	5	10

Table 4
Optimal CMN 2 for Case Study 1 showing basalt allocation (in kt).

Source	Sink					Surplus
	1	2	3	4	5	
1	75					
2		15				10
3			20	15	5	

Table 5
Source data for Case Study 2.

Source	Annual Capacity (kt/y)	Operating Life (y)	Cumulative Output (kt)
1	0.75	40	30
2	0.80	25	20
3	1.25	20	25
4	1.00	15	15
5	1.67	12	20

pinch, and it can be seen that the SCC extends beyond the DCC by a horizontal distance of 10 kt. The latter figure gives the amount of crushed basalt that cannot be accommodated within the system due to a sink deficit. There are different practical interpretations possible here. One option is to reduce the annual output of the rightmost source by 25% to eliminate this surplus; this action is possible in a green-field scenario where the crushing plants are yet to be built. Alternatively, the original annual capacity can be retained, and this excess material can be exported to a different system in a larger multi-zone problem. The latter scenario can be explored in future extensions of this methodology. The optimal network is shown in Table 3 as a source-sink matrix, and can be determined either via S8 or by direct inspection of Fig. 4. The sinks above the pinch (Sinks 4 and 5) are shaded in gray.

It is also possible to determine alternative optimal networks, such as that shown in Table 4. The occurrence of multiple alternative solutions has important engineering implications for the operation of terrestrial CMNs. In practice, the links in the enhanced weathering CMN are transportation routes along which crushed basalt is moved from crushing plants to application sites. It may be noted that the number of transportation routes is reduced to 5 in the alternative network (Table 4). One possible mode is transport by truck, which gives the network more flexibility for changing configuration in response to future events. Alternative solutions can be very useful in the event of disruptions in the road network used to transport the material. The flexibility to adjust configuration in response to natural (e.g., flooding) or man-made (e.g., road accidents) events makes the terrestrial RCN more resilient.

Table 6
Sink data for Case Study 2.

Sink	Annual Capacity (kt/y)	Cumulative Output (kt)	Minimum Operating Life (y)
1	1.00	50	50
2	0.50	20	40
3	0.40	10	25
4	2.00	30	15
5	0.50	5	10
6	1.25	10	8

6. Case study 2: biochar application

This second case study is intended to illustrate the structural similarity of biochar application with enhanced weathering CMNs. The data for the sources and sinks are given in Tables 5 and 6. As in the previous case study, the application limits at the sinks are assumed to consider physical, environmental, and socio-economic dimensions. The raw data have already been sorted as required in steps S1 and S2. The CO_2 sequestration factor is assumed to be 3.3 kt CO_2/kt biochar applied, which corresponds to biochar with 90% carbon content.

Implementing steps S3 and S4 gives Fig. 5. This result also provides an infeasible solution since the SCC is above the DCC. Using S5 to translate the SCC by 23 kt results in the optimal solution shown in Fig. 6. This time, there is a unique pinch point (shown in green) between Sinks 3 and 4 on the DCC. The horizontal span of overlap of the SCC and DCC is 102 kt, which gives the cumulative amount of biochar that can be applied within the system to sequester carbon. Based on S6, the corresponding cumulative CDR is 336.6 kt.

Based on S7, the significance of the pinch point is as follows. Sinks 1–3 lie below the pinch, and the 23 kt target represents the surplus of the cumulative application limit of these application sites; only 71.3% of their total storage capacity can be used. Sinks 4–6 all lie above the pinch point, and the SCC extends beyond the DCC by a horizontal distance of 8 kt, which is the amount of biochar that cannot be stored in any of the sinks within the system. Three alternative optimal CMNs generated using S8 are shown in Tables 7–9, again with sinks above the pinch being shaded in gray. All these networks satisfy the targets, but suggest

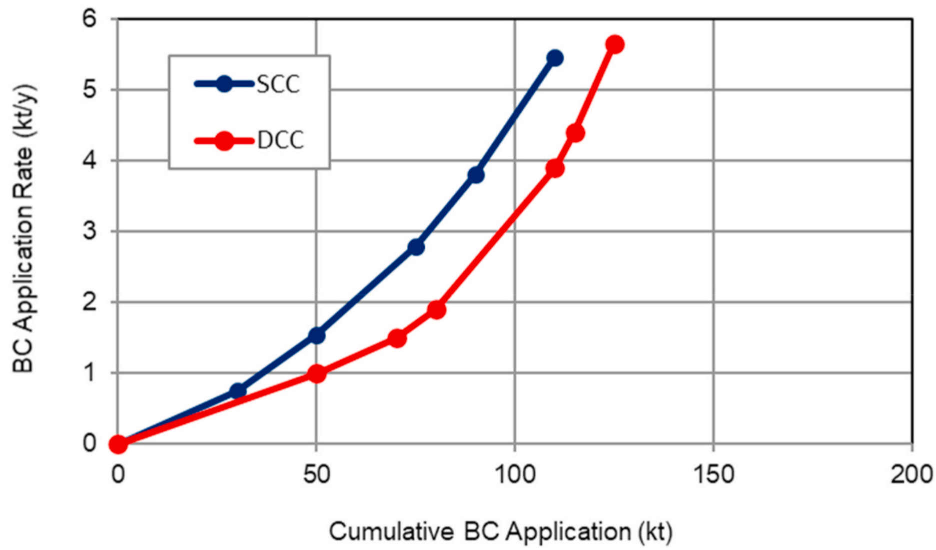

Fig. 5. Initial orientation of SCC and DCC for Case Study 2.

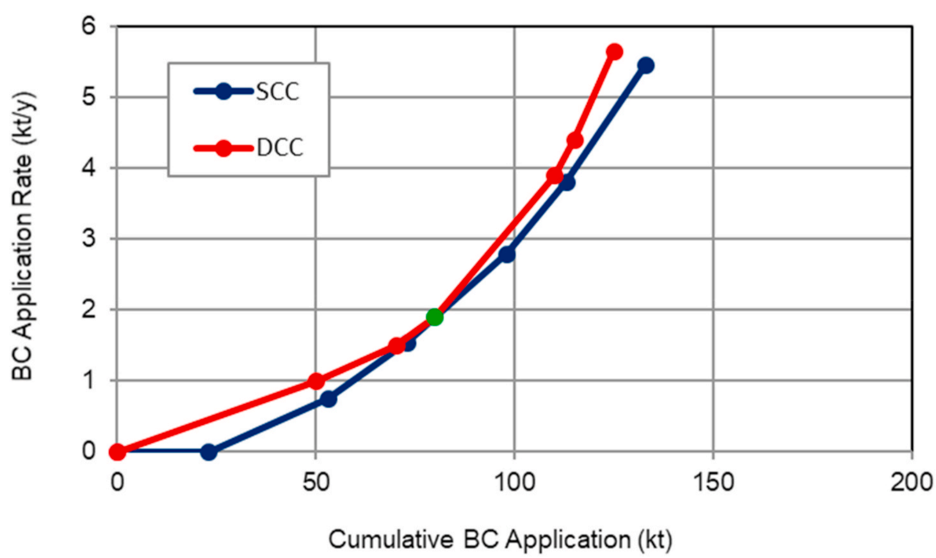

Fig. 6. Pinch diagram showing optimal solution for Case Study 2.

Table 7
Optimal CMN 1 for Case Study 2 showing biochar allocation (in kt).

Source	Sink						Surplus
	1	2	3	4	5	6	
1	30						
2	6.3	12.5	1.3				
3			7	18			
4				12	3		
5					2	10	8

different transportation routes. The first two networks (Tables 7 and 8) involve 10 transportation routes and the last one (Table 9) involves only 9 transportation routes. The practical implications of these alternative results are similar to those discussed in Case 1. Alternative optima provide flexibility and resilience in the event of future operational disruptions to the transportation routes.

Table 8
Optimal CMN 2 for Case Study 2 showing biochar allocation (in kt).

Source	Sink						Surplus
	1	2	3	4	5	6	
1	30						
2	6.3	12.5	1.3				
3			7	18			
4						7	8
5				12	5	3	

Table 9
Optimal CMN 3 for Case Study 2 showing biochar allocation (in kt).

Source	Sink						Surplus
	1	2	3	4	5	6	
1	10	20					
2	10		10				
3	7			15			3
4					5	10	
5				15			5

7. Conclusions

This work has developed a novel pinch analysis approach to planning CMNs based on either enhanced weathering or biochar application. Both of these NETs can be implemented via optimal matching of multiple sources (plants) and sinks (application sites) within the CMN. Pinch analysis enables the identification of optimal targets and network topologies to maximize carbon sequestration in these systems. Case studies on enhanced weathering and biochar application were solved to illustrate the capability of this approach. Pinch analysis principles enable the systems to be decomposed into regions above and below the pinch point; the decomposition gives insights on engineering implications for flexible CMN operations, as illustrated by the solved examples. This methodology offers the prospect of a simple but powerful planning tool for large-scale implementation of terrestrial NETs in carbon management initiatives.

In the future, potential extensions of this work can be explored. Modified pinch analysis approaches can be developed to handle non-concurrent operations of sources and sinks, non-deterministic system parameters, and multiple zones. Alternative PI approaches based on automated targeting or superstructure models can also be developed to handle more detailed scenarios. Simultaneous enhanced weathering and biochar application at the same site can be explored to take advantage of possible synergistic effects. In the case of partial incompatibility between the two NETs (i.e., only one can be used at a given site), the resulting system can be framed as a special class of segregated targeting problems. The pinch analysis methodology can also be combined with tools such as mathematical programing or game theory to give hybrid computing approaches, and can be integrated into a broader NET planning framework that considers different emissions and environmental footprints.

Declaration of competing interest

The authors declare that we have no conflicts of interest.

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