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A Two-Stage Optimization Model for the Synthesis of Biochar-Based Carbon Management Networks

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Biochar, a product obtained from pyrolysis of residual biomass, can be deliberately applied to soil to sequester carbon from the atmosphere and simultaneously improve soil fertility. These benefits can be potentially scaled up through biochar-based management networks. Such systems have a potential to store carbon dioxide in the long run and can thus contribute significantly to mitigate global climate change. These systems pave the way to systematically allocate biochar streams of different quality levels to various sinks, such as agricultural lands which may have tolerance limits on the amount of contaminants in biochar. In this work, a two-stage optimization model is proposed to determine the source-sink allocation of biochars while simultaneously ensuring that the land's quality requirements are attained. In the first stage, the system's total cumulative CO_2 sequestration is maximized. Then, a cost equation is incorporated in the model to minimize the system's total cost within the given time frame. A case study is solved to demonstrate the applicability of the developed model.

1. Introduction

Anthropogenic carbon dioxide emissions have been accelerating at a global scale, rising at a rate of more than 3 % annually since year 2000 (Solomon et al., 2009). If atmospheric carbon dioxide concentrations increase from current levels near 400 ppm to a peak of 600 ppm over the coming century, dangerous and irreversible impacts on Earth's ecosystems should be expected (Solomon et al., 2009). It is thus necessary to ensure that further economic growth should follow low-carbon trajectories (Lee et al., 2017). Withdrawal of excess CO_2 from the atmosphere is a significant mitigation strategy that would assume greater importance when compared to equivalent reduction in emissions. In this regard, biochar, a traditional strategy for soil amendment has recently received substantial attention in the scientific world due to its significant potential to combat climate change because it results in the net transfer of carbon dioxide from the atmosphere into the ground.
Biochar can be produced from various feedstock materials via a range of thermochemical conversion pathways that yield different proportions of biochar and bioenergy products such as bio-oil and syngas (Vereš et al., 2014). The biochar that is formed is a carbon-rich solid which is comprised of labile (degradable) and recalcitrant (unreactive) fractions. The carbon in biochar is derived from atmospheric CO_2 fixed in biomass via photosynthesis. The primary reason for the stability of biochar in soils is their chemical recalcitrance, which is due to aromatic structures of varying properties (Hillel and Rosenzweig, 2010). This is a relevant measure for its ability to prevent photosynthetically fixed carbon from being returned quickly to the atmosphere. The stable storage of biochar in soils represents a long-term removal of atmospheric carbon due to the fact that the recalcitrant fraction present in biochar decomposes very slowly, typically with a half-life measured on the time scale of a few centuries (Hillel and Rosenzweig, 2010). Hence, the production and application of biochar in soil is a significant carbon sequestration strategy and has been suggested as one possible means of reducing the atmospheric CO_2 concentration (Woolf et al., 2010). In a case study conducted by Field et al. (2013), it is indicated that slow pyrolysis systems can possibly mitigate up to 1.4 Mg CO_2eq/t feedstock consumed. Moreover, life cycle assessment (LCA) of biochar was performed by Bartocci et al. (2016) and the final carbon footprint was evaluated to be equal to − 737 kg CO_2eq/t of feedstock (miscanthus) dried. It is also notable that the application of biochar in soil improves the physical, chemical and biological properties of soil such as

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increase in soil-water and nutrient holding capacities that result in improved crop yields (Jeffery et al., 2011) and reduction of the need for fertilizers which in turn enhances the amount of carbon removed from the atmosphere (Woolf et al., 2010). There are contradictory reports from different researchers about the co-beneficial effects of biochar (Kuppusamy et al., 2016). Unintended consequences of biochar application include oversupply of nutrients, increase in soil pH, impacts on germination and soil biological processes, binding and deactivation of agrochemicals (herbicides and nutrients) in soil, and release of toxic chemicals that may be present in biochar (e.g., heavy metals, polycyclic aromatic hydrocarbons (PAHs), and dioxins) (Kookana et al., 2011). However, in the literature there is lack of evidence on whether and at what amount of contaminants present in biochar may pose a threat to plants and other living organisms when applied to soil (Kołtowski and Oleszczuk, 2015). Key areas of research needed include characteristics of biochar to avoid ecotoxicological impacts, effects of biochar on nutrient and contaminant behaviour, effects of decomposition, and the influence of feedstock and pyrolysis conditions on biochar properties (Kookana et al., 2011). These agronomic and environmental risks imply that there is a need to strategically match biochar sources (i.e., pyrolysis plants and the associated feedstocks and process conditions) with biochar sinks (i.e., agricultural lands and the associated local soil conditions) in order to minimize the adverse effects of biochar application to soil (Tan, 2016). This paper develops an extension of the previous model developed by Tan (2016) for the optimum allocation of biochar for carbon sequestration. This work advances from the previous paper by proposing a second optimization stage. The two-stage optimization model is used to determine the source-sink allocation of biochars, while simultaneously ensuring that the land's quality requirements are attained. Furthermore, multiple contaminants that may be present in biochar are incorporated in the model as stream "quality" constraints. In the first stage, the system-wide net CO_2 sequestration is maximized. The maximum amount of net CO_2 sequestered is then added as a new constraint to the problem in the second stage of optimization wherein the total system cost is to be minimized, an aspect that which was neglected in the work of Tan (2016). The framework can be used as a decision-support tool to guide the high-level planning and implementation of biochar source–sink networks. This paper consists of four subsequent parts. In the first part, a formal problem statement is described. Then, a discussion of the optimization model formulation is presented. A hypothetical case study is explored to demonstrate the applicability of the mathematical model. Conclusions are given in the final part of this paper.

2. Formal problem statement

The formal problem statement can then be stated as follows: Given a set of biomass processing plants designated as sources $i \in I\ (i = 1,2,3 \ldots M)$ with available amount of biochars to be allocated to a set of agricultural lands or other tracts of land designated as sinks $j \in J\ (j = 1,2,3 \ldots N)$ during the given time frame with time intervals $p \in P$ (one-year periods, $p = 1,2,3 \ldots T$); given that every source i is characterized by annual flowrate limits and levels of impurities $k \in K$ (contaminants, $k = 1,2,3 \ldots Q$) are known; given that every sink j can only accept up to a known maximum annual flowrate, maximum total storage capacity and maximum allowable level of each impurity k; given that, for each potential match between source i and sink j, the carbon footprint associated with the handling and transportation of each unit of biochar is known; the problem is formulated to find the optimum allocation of biochar coming from each source i to each sink j in each time interval p whose objectives are to maximize the system-wide net CO_2 sequestration and minimize the total system cost.

3. Mathematical model formulation

The MILP model used to synthesize the biochar source-sink network is given by Eq(1) – (10). The problem is defined as a two-stage optimization approach. In the first stage, the objective function is to maximize the total cumulative CO_2 sequestration within the given time frame:

$$\text{maximize} \qquad \Sigma_i \Sigma_j \Sigma_p A_i x_{ijp} - \Sigma_i \Sigma_j \Sigma_p B_{ij} x_{ijp} \tag{1}$$

Parameter A_i is the sequestration factor of biochar coming from source i which gives the amount of CO_2 sequestered per unit mass of biochar (t CO_2/t). The coefficient B_{ij} represents the CO_2 emissions per unit mass of biochar which is the penalty incurred for transporting and handling the biochar (also in t CO_2/t) from source i down to its final destination sink j. The variable x_{ijp} expressed in t/y is the allocated amount of biochar from source i to sink j in period p.
Next, the source balance is given by:

$$\Sigma_j x_{ijp} = s_{ip} \qquad \forall i, p \tag{2}$$

where s_{ip} is the total amount of biochar produced from source i in period p and is expressed in t/y. The following equation depicts the higher and upper limits of this quantity:

$$b_i s_{ip}^L \leq s_{ip} \leq b_i s_{ip}^U \qquad \forall i, p \tag{3}$$

$$b_i \in \{0,1\} \qquad \forall i \tag{4}$$

where b_i is a binary variable signifying the existence $(b_i = 1)$ or non-existence $(b_i = 0)$ of source i at any time within the given time frame while s_{ip}^L and s_{ip}^U are the lower and upper limits of biochar production rate from source i respectively. Variable b_i becomes zero if a value of s_{ip} that falls within the bounds cannot be found. Then, the biochar balances at the sinks are defined by the equations below:

$$\Sigma_i x_{ijp} \leq D_{jp} \qquad \forall j, p \tag{5}$$

$$\Sigma_i \Sigma_p x_{ijp} \leq L_j \qquad \forall j \tag{6}$$

$$\Sigma_i x_{ijp} Q_{ikp} \leq D_{jp} Q_{jk}^* \psi \qquad \forall j, k, p \tag{7}$$

where D_{jp} is the limiting biochar application rate from sink j in period p and is expressed in t/y, L_j is the total biochar storage capacity of sink j and is given in t, Q_{ikp} is the concentration of contaminant k present in biochar produced from source i in period p, Q_{jk}^* is the maximum level of contaminant k in biochar that can be tolerably applied to the soil in sink j, and ψ is a dimensionless risk aversion parameter that can assume values from zero to one. The levels of contaminant are expressed in ppm or g/t. The parameter ψ is a measure of the extent to which the decision maker is ready to risk soil contamination. Its value can be set to zero if no level of soil contamination can be tolerated and one if the decision maker is willing to accept the soil contaminant levels to reach the given limit. Finally, limits are set on all flowrates between source-sink pairs:

$$0 \leq x_{ijp} \leq b_{ij} s_{ip}^U \qquad \forall i, j, p \tag{8}$$

$$b_{ij} \in \{0,1\} \qquad \forall i, j \tag{9}$$

where b_{ij} is a binary variable denoting the existence $(b_{ij} = 1)$ or non-existence $(b_{ij} = 0)$ of a stream of biochar from source i to sink j. In stage 2 of the optimization, where the total system cost (TSC) is to be minimized, the maximum total cumulative CO_2 sequestration is added as a new constraint to the problem. Note that all other constraints are exactly the same as those in stage 1. The objective function in the second stage of optimization is given by:

$$\text{minimize} \qquad TSC = \Sigma_i \Sigma_j \Sigma_p PC x_{ijp} + \Sigma_i \Sigma_j \Sigma_p \frac{x_{ijp}}{Vc} \times 2 d_{ij} Cv + \Sigma_i \Sigma_j \Sigma_p AC x_{ijp} \tag{10}$$

where PC is the production cost per unit mass of biochar and is expressed in US$/t, Vc is the capacity of vehicles required to transport the total amount of biochar and is given in t/vehicle, d_{ij} is the transportation distance in km from source i to sink j multiplied by 2 to denote round trip, Cv is the specific vehicle transport cost and is expressed in US$/km, and AC is the cost of biochar application to soil per unit mass of biochar and is given in US$/t. The problem stated herein is given by a MILP model. For a more detailed discussion of the original problem formulation, the reader is referred to the paper of Tan (2016). The application of the extended model is clearly illustrated in the succeeding section.

4. Illustrative case study

The illustrative example is adapted from the paper of Tan (2016) with some modification. The hypothetical case study depicts three sources, four sinks, three contaminants and a time frame of 10 years. The objective of this section is to facilitate clear understanding on the application of the model described above. The case study also uses credible assumptions based on the current related literature on biochar. The contaminants being considered here are PAH and heavy metals such as Zn and Pb which pose a potential drawback over the utilization of biochar for amendment of soils used for crop plant cultures due to ecotoxicity risk (Kuppusamy et al., 2016). Table 1 shows the source data for the three biochar processing plants while the characteristics of the four sinks are given in Table 2. The storage capacity of each sink is considered to be the amount of biochar that can be stored until the soil is saturated. The annual limit to the rate of biochar application is also assumed to be one-tenth of the storage capacity for the 10-year time frame. The last three columns of Table 2 give the maximum levels of the three contaminants in biochar that can be safely added to the soil. Table 3 shows the distances between the biochar sources and sinks. In this case study, Tan (2016) assumed that the carbon emission footprint of transporting biochar by truck is 0.1 kgCO_2/t/km based on the paper of Foo et al. (2013). The cost data for the case study are presented in Table 4. At present, there is no major industrial biochar market from which to obtain biochar price and cost data for a comprehensive estimation (Ahmed et al., 2016). Production

cost is related mainly to equipment cost. Ahmed et al. (2016) listed some of the production costs estimated by different researchers. Hence, it is assumed here that the production cost is the average of all the values reported in the literature. For simplicity, the production cost is fixed at US$ 886.75/t. Meanwhile, the unit cost of biochar application to soil is estimated by Kulyk (2012) at US$ 6.58/t. The MILP model described above was employed using the commercial optimization software LINGO 14.0 and solved with negligible CPU time using a laptop with 3.00 GB RAM, i3 CPU M 380 and a 64-bit operating system running on Windows 7 Home Basic.

4.1 Baseline scenario

The mathematical optimization was performed and the resulting optimal allocation of biochar for baseline scenario ($\psi = 1$) is presented in Table 5. Note that the results for all optimization variables remain the same for both stages. This means that the synthesized biochar source-sink network has the same structure for both maximum CO_2 sequestration and minimum system cost. Two values are given in each cell; the first one gives the biochar allocation during the first two years of operation, while the second number gives the biochar allocation from the third to the tenth years. Commencement of operation of Source 3 from the 3rd y onward results in a modified allocation for the remainder of the 10-year planning horizon, as indicated by the second set of numbers in each cell of Table 5. In this case, the allocation network is more complex and requires blending of biochar. The model recommends blending of biochar at sink 1 from the third to the tenth years of operation and at sink 4 in the entire 10 y planning horizon to ensure that the limits set for the contaminants are not exceeded. For example, it can be proven from simple material balance calculation at sink 1 that 326.67 t/y of biochar from source 1 (with PAH, Zn and Pb levels of 10, 50, 2 g/t) blended with 200 t/y of biochar from source 2 (with PAH, Zn and Pb levels of 2, 10, 1 g/ty) and 333.33 t/y of biochar from source 3 (with PAH, Zn and Pb levels of 1, 5, 0.5 g/t) results in a stream of 860 t/y with PAH, Zn and Pb levels of 4.650, 23.256, and 1.186 g/t. PAH, Zn and Pb limits are set at 25,000, 20,000, and 4,000 g/y at sink 1. The effective rate of CO_2 sequestration during the first 2 yis 6,693.38 t/y; this net value results from 6,712 t/y of CO_2 sequestration via direct biochar application minus a small penalty of 20.12 t/y of emissions from transportation. During the final 8 y of operation of the biochar system, the net sequestration rate is 13,520.03 t/y which results from 13,551.916 t/y of sequestration from biochar, minus 31.886 t/y of emissions from biochar transport. During the 10-y period of operation, the net CO_2 sequestration achieved by the system is 121,544 t, which consists of the biochar CO_2 sequestration of 121,839.33 t (6,712 t/y x 2y + 13,551.916 t/y x 8y) minus the total transportation penalty of 295.33 t (20.12 t/y x 2y + 31.886 t/y x 8y). The total system cost (TSC) during the 10-y period of operation is US$ 47,887,520.00.

Table 1: Biochar source data for the case study.

Source	Minimum production rate (t/y)	Maximum production rate (t/y)	Sequestration factor (t CO2/t)	Biochar quality (mg PAH/kg)	Biochar quality (mg Zn/kg)	Biochar quality (mg Pb/kg)	Years of operation
1	1,500	2,000	2.2	10	50	2	1-10
2	1,000	1,200	2.0	2	10	1	1-10
3	2,500	3,000	2.5	1	5	0.5	3-10

Table 2: Biochar sink data for the case study.

Sink	Area (ha)	Application Dosage (t/ha)	Storage Capacity (t)	Limiting Biochar Flowrate (t/y)	Limiting Biochar Quality (mg PAH/kg)	Limiting Biochar Quality (mg Zn/kg)	Limiting Biochar Quality (mg Pb/kg)
1	200	50	10,000	1,000	25	20	4
2	500	20	10,000	1,000	10	125	3
3	400	25	10,000	1,000	5	10	2
4	1,000	30	30,000	3,000	2	50	2

Table 3: Transportation distances in km for source-sink pairs in the case study.

Source	Sink			
	1	2	3	4
1	70	60	50	120
2	80	60	40	50
3	100	80	80	40

Table 4: Cost data for the case study.

Parameter	Values
Production cost (PC)	US$ 886.75/t
Capacity of vehicle (Vc)	25 t
Specific vehicle transport cost (Cv)	US$ 1.535/km
Biochar application cost (AC)	US$ 6.58/t

Table 5: Optimal source-sink network for the baseline scenario of the case study (biochar flowrates in t/y).

Source	Sink				
	1	2	3	4	Total
1	400, 326.67	1000, 1000	200, 0	360, 333.33	1960, 1660
2	0, 200		0, 1000	1200, 0	1200, 1200
3	0, 333.33			0, 2666.67	0, 3000
Total	400, 860	1000, 1000	200, 1000	1560, 3000	

4.2 Optimal system cost with respect to ψ

The corresponding MILP model is solved for the different values of $\psi = 0.9, 0.8, \ldots 0.2, 0.1$ and the selected network corresponding to $\psi = 0.8$ is presented in Table 6. The results for all optimization variables remain the same for both stages. It is interesting to note that the production of low-quality biochar from Source 1 is reduced at $\psi = 0.8$ and is completely eliminated for $\psi = 0.6, 0.4 \text{ and } 0.2$. Figure 1 shows the plot of the optimal total system cost versus the risk aversion parameter ψ. A rapid increase in the magnitude of total system cost occurs as ψ is increased further above the value of 0.7. On the other hand, the value decreases more rapidly as ψ is reduced further below 0.3.

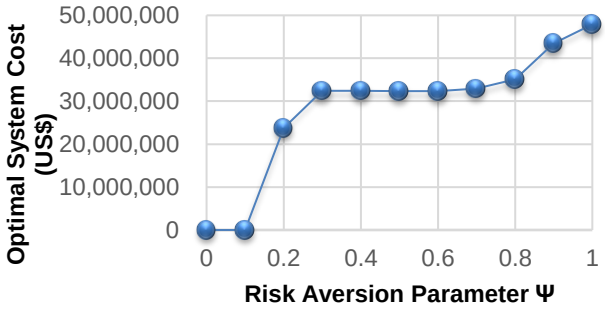

Figure 1: Optimal system cost versus the parameter ψ.

Table 6: Optimal source-sink network for $\psi = 0.8$ (biochar flowrates in t/y).

Source	Sink				
	1	2	3	4	Total
1	320, 0	800, 0	160, 0	240, 0	1520, 0
2		0, 400	0, 800	1200, 0	1200, 1200
3				0, 3000	0, 1300
Total	320, 0	800, 400	160, 800	1440, 3000	

5. Conclusions

A two-stage optimization MILP model for the synthesis of biochar-based carbon management networks was developed in this work. In the first stage, the system-wide net CO_2 sequestration is maximized. Subsequently, CO_2 sequestration is added as a new constraint in the second stage to minimize the total system cost. The multi-period source-sink model formulation allows the biochar streams that contain multiple contaminants of varying impurity levels to be blended and allocated to minimize the total system carbon footprint and simultaneously ensure that the tolerable limits of farms or tracts of land designated as carbon sinks are not exceeded. The model also enables the determination of the total system cost when the total cumulative CO_2

sequestration is maximized. The proposed MILP model can serve as a fundamental framework to develop a more complex formulation in the future to aid in the high-level planning and implementation of a larger scale biochar-based carbon sequestration networks. Future work can further put emphasis on the development of multiple-objective extensions in which new parameters, variables and constraints are incorporated to reflect economic aspects as well as various supply chain sustainability metrics used in the literature.

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References

Ahmed, M. B., Zhou, J. L., Ngo, H. H., Guo, W. 2016, Biomass and bioenergy insight into biochar properties and its cost analysis. Biomass and Bioenergy, 84, 76–86.

Bartocci, P., Bidini, G., Saputo, P., Fantozzi, F., 2016, Biochar Pellet Carbon Footprint, Chemical Engineering Transactions, 50, 217–222.

Field, J. L., Keske, C. M. H., Birch, G. L., Defoort, M. W., Francesca Cotrufo, M., 2013, Distributed biochar and bioenergy coproduction: A regionally specific case study of environmental benefits and economic impacts, GCB Bioenergy, 5, 177–191.

Hillel, D., Rosenzweig, C., 2010. Handbook of Climate Change and Agroecosystems (Vol. 1), Imperial College Press, London, UK, ISBN: 10 1-84816-655-9.

Jeffery, S., Verheijen, F. G. A., Van Der Velde, M., Bastos, A. C., 2011, Agriculture , Ecosystems and Environment: A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis, Agriculture, Ecosystems and Environment, 144, 175–187.

Kołtowski, M., Oleszczuk, P., 2015, Toxicity of biochars after polycyclic aromatic hydrocarbons removal by thermal treatment, Ecological Engineering, 75, 79–85.

Kookana, R., Sarmah, A., Van Zwieten, L., Krull, E., Singh, B., 2011, Biochar application to soil: agronomic and environmental benefits and unintended consequences, Advances in Agronomy, 112, 103-143.

Kulyk, N., 2012, Cost-Benefit Analysis of the Biochar Application in the U.S. Cereal Crop Cultivation. Capstone Project, School of Public Policy Capstones, 12, University of Massachusetts, Amherst, USA.

Kuppusamy, S., Thavamani, P., Megharaj, M., Venkateswarlu, K., Naidu, R., 2016, Agronomic and remedial benefits and risks of applying biochar to soil: Current knowledge and future research directions, Environment International, 87, 1–12.

Lee, C. T., Hashim, H., Ho, C. S., Van Fan, Y., Klemeš J.J., 2017, Sustaining the low-carbon emission development in Asia and beyond: Sustainable energy, water, transportation and low-carbon emission technology, Journal of Cleaner Production, 146, 1-13.

Solomon, S., Plattner, G.K., Knutti, R., Friedlingstein, P., 2009, Irreversible climate change due to carbon dioxide emissions, Proceedings of the National Academy of Sciences of the United States of America, 106, 1704–1709.

Tan, R. R., 2016, A multi-period source-sink mixed integer linear programming model for biochar-based carbon sequestration systems, Sustainable Production and Consumption, 8, 57–63.

Vereš, J., Kolonicný, J., Ochodek, T., 2014, Biochar status under international law and regulatory issues for the practical application, Chemical Engineering Transactions, 37, 799–804.

Woolf, D., Amonette, J.E., Street-Perrott, F.A., Lehmann, J., Joseph, S., 2010, Sustainable biochar to mitigate climate change, Nature Communications, doi: 10.1038/ncomms1053.