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Biomass transport cost from field to conversion facility when biomass yield density and road network vary with transport radius

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HIGHLIGHTS

- Previous biomass models have limitations due to constant biomass distribution assumption.
- Formula is developed that is capable of approximating variations in biomass distribution.
- *Transport Amplification Factor* ψ integrates variations in biomass distribution and tortuosity.
- Using simulation, ψ is simplified to linear relationship with biorefinery size.
- Biomass transport cost increases with variations in its spatial distribution.

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ABSTRACT

Biomass transport cost from field to a conversion facility is a major component of biofuel production cost. Several studies have provided a general framework, independent of location, for maximising cost competitiveness of bioenergy plants. The majority of these studies assume uniform spatial distribution of biomass and road network, independent of the size of the biorefinery. Although this assumption simplifies the theoretical derivation, it may not be suitable for practical cases. We develop a more generic biomass transport model that allows biomass yield density and road network vary with transport radius, and then derive a formula for determining biomass transport cost, which more accurately represents changes in biomass transport cost with conversion plant capacity. The formula can be used to evaluate locations and investment opportunities in large scale biofuel production.

1. Introduction

Bioenergy has gained increasing attention recently because of its potential for mitigating greenhouse gas emissions, enhancing energy security, and promoting rural economic development when sustainably produced. The potential of biomass for energy is massive, ranging from 33 to 1135 EJ yr^{-1} in about 50 yr worldwide [1]. This is equivalent of 5–185 billion barrels of oil, enough to meet the global energy requirement of 820 EJ yr^{-1} by 2040 [2]. The US alone can produce over 1.6 billion dry tonnes of terrestrial biomass annually, while continuing to meet demand for food and feed [3]. An analysis by Sandia National Laboratories and the General Motors R&D Centre concluded that 90 billion gallons (341 billion l) of biofuel can be produced each year in the US [4]. These have led to an increasing interest in the bioenergy sector globally.

Biofuel development involves growing and harvesting biomass, transporting biomass to a conversion plant (biorefinery), converting biomass to bioenergy and bioproducts, and finally delivering end products to distribution centres or markets. Along the biofuel value chain, biomass transport cost from field to a biorefinery is a significant component of biofuel production cost. Extensive studies have been done at several locations, using actual biomass distribution and regional transportation networks [5–9]. These studies show biomass yield density M (t ha^{-1} yr^{-1}) varies with biomass supply distance r (km) from the biorefinery. This density variation has a significant impact on biomass transport cost. To reduce biomass transport cost, optimal biorefinery locations should be near the centres of the regions of high biomass yield density.

Another important factor impacting biomass transport cost is tortuosity factor τ, which is the ratio of actual travel distance to the shortest straight line distance. Studies focusing on the assessment of tortuosity factor τ and considering real road network, have shown that τ varies considerably with biorefinery capacity [10].

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Yet, previous studies using a general framework for determining biomass transport cost do not integrate variations in biomass yield density and tortuosity factor with biomass supply radius [11–20]. These studies have considered biomass to be available with a uniform yield density around the biorefinery, and a constant tortuosity factor that is independent of biorefinery capacity or supply radius. Although this assumption simplifies the theoretical model, it reduces the applicability of the model to the real world situations where biomass yield density and tortuosity factor are rarely constant.

In this paper, we advance these previous studies by assuming biomass yield density and tortuosity factor can vary with biomass supply distance from the biorefinery. In the first part of the remaining paper, we approximate biomass yield density M and tortuosity factor τ to linear functions of supply distance r from the biorefinery using Taylor approximation. This approximation is validated using data drawn from actual cases of biomass distribution and regional transportation networks in the existing literature. In the second part, a more general biomass transportation formula is presented that integrates the relationship between biomass yield density, tortuosity factor τ, and biomass supply radius. The formula can be applied to various biomass types for analysing biomass transport cost, optimal biorefinery size, and biomass supply radius. Our work bridges the knowledge gap in estimating biomass transport cost that is not addressed by previous studies, thus extending its applicability to broader situations.

2. Methods and materials

Symbols and units

R (km) is the biomass supply radius, determined by biorefinery capacity,
r (km) is any linear distance from the biorefinery,
S (t yr^{-1}) is the capacity of the biorefinery,
M_r (t ha^{-1} yr^{-1}) is the biomass yield density at linear distance r from the biorefinery,
τ_r is tortuosity factor (ratio of actual road distance to linear distance) at linear distance r (km) from the biorefinery

2.1. Relationship between biomass yield density M and distance from biorefinery r

Significant variation in biomass yield density exists even in regions of high biomass availability. This is due to variability in land productivity, land use for agriculture or other purposes, plant species diversity, or resource availability [21]. To reduce biomass transport cost, it is logical to locate biorefineries near the centres of the regions of high biomass yield density, and this necessitates the need for determining the optimal location of a biorefinery.

Biomass yield density M_r at a distance r from a biorefinery can be therefore defined as a function of r, denoted by $M(r)$. Since the function $M(r)$ can vary by location, we use Taylor series polynomial that is capable of approximating any arbitrary function about a point, by representing a function as an infinite sum of terms calculated from the function's derivatives [22]. Using Taylor series polynomial representation for $M(r)$ about a point a, biomass yield density at distance r from the biorefinery can be represented as

$$M(r) = M(a) + M'(a)(r-a) + M''(a)\frac{(r-a)^2}{2!} + M'''(a)\frac{(r-a)^3}{3!}\dots, \tag{1}$$

where $M(a)$ is the biomass yield density at distance a from the biorefinery. The biomass yield density function $M(r)$ is then analysed using the actual distribution of biomass around the optimally located biorefinery, to identify the order of Taylor series approximation for simplification of function $M(r)$. Examples of similar approach to approximate Taylor series polynomial using the first and second order derivatives are available in literature [23,24].

The data reported in several previous studies are used to validate the application of Taylor series approximation. They include studies in the US states of North Dakota [5] and Michigan [7], Northern Sweden [6], Southern Finland [9], and India [8]. For studies where biomass yield density $M(r)$ is not directly available, a biorefinery is assumed at the centre of a circular area divided into several circular zones ($A_1, A_2, \dots$) with outer radii ($R_1, R_2, \dots$) as in Fig. 1. The biomass yield density of each zone ($M_1, M_2, \dots$) is calculated from biomass available y_r (t yr^{-1}) at linear distance r, using Eqs. (2–4).

$$A_P = \pi R_P^2 - \pi R_{P-1}^2, \tag{2}$$

where A_P is the area between radii R_P and R_{P-1}.

$$Y_P = \sum_{\text{Distance } R_{P-1}}^{\text{Distance } R_P} y_r, \tag{3}$$

where Y_P is biomass available between radii R_P and R_{P-1}.

$$M_P = \frac{Y_P}{A_P}, \tag{4}$$

where M_P is biomass yield density between radii R_P and R_{P-1}.

Based on the regression analysis of $M(r)$ on r (Sections 2.1.1–2.1.4), it is found that Taylor series approximation to include only the first-order derivative explains majority variation. Hence, using Eq. (1) biomass yield density around the biorefinery that has been optimally located is approximated as

$$M(r) = M(a) + M'(a)r - M'(a)a. \tag{5a}$$

Using M_0 as the yield density close to the biorefinery, Eq. (5a) is simplified by letting $r = 0$ and then through some manipulations in Eqs. (5c) and (5d). That is,

$$M(0) = M(a) - M'(a)a, \tag{5b}$$

and then manipulating with Eqs. (5a) and (5b) yields,

$$M(r) = M_0 + M'(a)r. \tag{5c}$$

Since $M'(a)$ is a constant, Eq. (5c) can be further simplified to

$$M(r) = M_0 - C_1 r, \tag{5d}$$

where M_0 is the biomass yield density near the biorefinery, and C_1 is the rate of change in yield density M with distance r from the biorefinery.

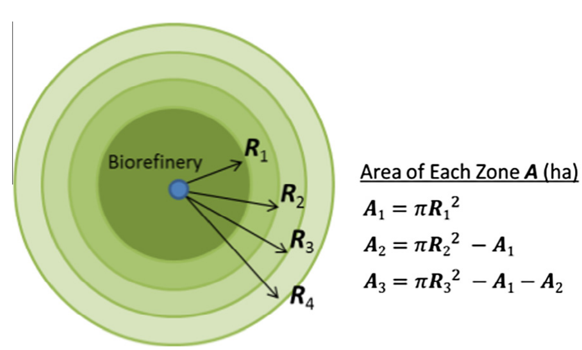

Fig. 1. Biomass distribution around a biorefinery.