Efficient and sustainable bioenergy production in Swedish forests

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Background

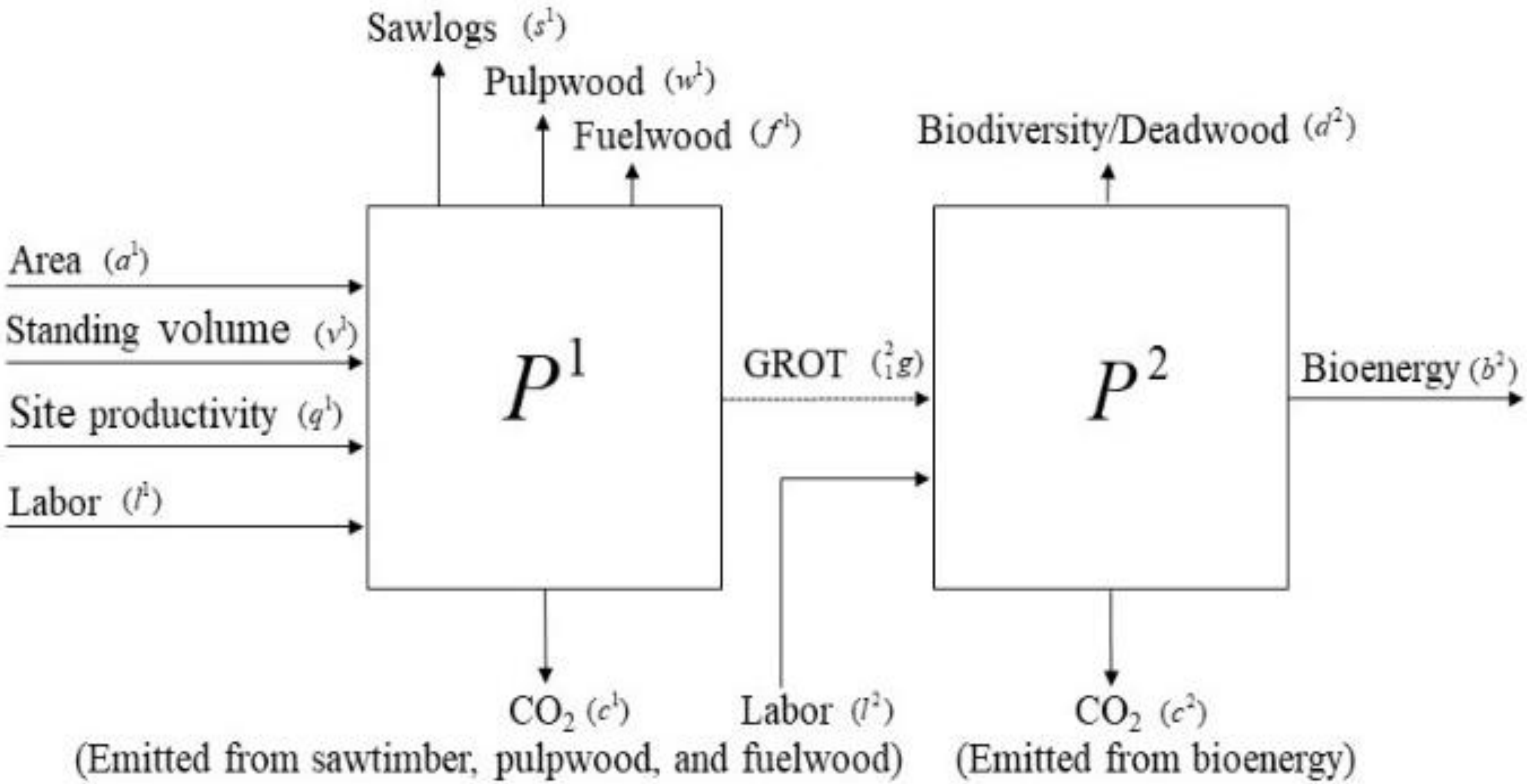
- Branches and tops (**GROT**) of harvested trees is a large part of forest biomass and has large potential for energy use
- Current production is supposedly **low**
- **Improving efficiency** in forest bioenergy production is a potentially cost-effective way to increase its supply

Purpose

- **Assess the efficiency** of bioenergy production in Swedish forests.
- Identify **where inefficient production is located**.
- What the production potentials would be **if inefficiency was removed**.
- We take a **network approach** to model these interconnected systems of forest products and biofuels production, forest habitat, and CO_2 emissions.

Methodology

A network DEA model



Data

Table 1. Input and output variables for the network DEA model

Technology	Type	Variable	Definition
P^1	Input	a^1	Area of productive forest land (1000 ha)
		q^1	Site productivity of productive forest land (m^3 standing volume/ha/year)
		v^1	Standing volume on productive forest land (million m^3 standing volume)
		l^1	Annual working units in forestry, which is the total number of working hours divided by 1800 hours, i.e., 1 AWU = 1800 hours
	Output	s^1	Volume of sawtimber of annual fellings (1000 m^3 solid volume under bark)
		w^1	Volume of pulpwood of annual fellings (1000 m^3 solid volume under bark)
		f^1	Volume of fuelwood of annual fellings (1000 m^3 solid volume under bark)
		g^1	Total GROT associated with fellings (1000 tonnes dry matter)
		c^1	Amount of carbon emitted from combustion of biproducts from sawtimber and pulpwood, and of fuelwood (1000 tonnes carbon)
P^2	Input	g^1	Total GROT associated with fellings (1000 tonnes dry matter)
		l^2	Overall cost of extracting GROT to end customer (SEK), including labor, transport cost and machine cost
	Output	d^2	Volume of deadwood left in forest (million m^3 over bark)
		b^2	Amount of bioenergy (1000 tonnes dry matter).
		c^2	Amount of carbon emitted from combustion of bioenergy (1000 tonnes carbon)

Data

Table 2. Descriptive statistics of inputs and outputs for Swedish forests at county level, 2008-2014

Variable	Mean	SD	Minimum	Maximum
Productive forest land area (a^1)	1115	959	159	3591
Site productivity (q^1)	7	2	3	11
Standing volume (v^1)	150	93	30	333
Annual working units (l^1)	779	426	268	2303
Sawtimber (s^1)	1666	818	367	3662
Pulpwood (w^1)	1539	751	339	2941
Fuelwood (f^1)	297	145	65	582
All GROT (g^1)	580	299	119	1259
Carbon stored in annual growth in 1000 tonnes carbon (C_a)	1610	920	360	3301
Carbon in bi-products of sawtimber and pulpwood, and fuelwood that is burned as energy (c^1)	369	180	83	756
Cost of extracting GROT (l^2)	79	48	11	217
Deadwood (d^2)	9	7	1	28
Bioenergy (b^2)	69	40	11	193
Carbon in bioenergy (c^2)	34	19	5	95
Sawtimber price in SEK/m³f excl. bark (p^s)	493	73	382	651
Pulpwood price in SEK/m³f excl. bark (p^w)	307	46	248	404
Fuelwood price in SEK/m³f (p^f)	412	53	344	507
Bioenergy price in SEK/tonne dry matter (p^b)	941	122	785	1157

DEA model →

$$R_{k'}^{*} = \max_{z_k^1, z_k^2, b^1, s^1, w^1, f^1} \left(\sum_{y} p_{k'}^{y} y^1 + p_{k'}^{b} b^2 + p_c C_a^{k'} - p_c (c^1 + c^2) \right)$$

$$\begin{aligned}
s.t. \quad & \sum_{k=1}^{K} z_k^1 y_{km}^1 \geq y_m^1, \ m = 1, \ldots, M, & (P^1) \\
& \sum_{k'}^{K} z_k^1 c_k^1 = c^1, & \\
& \sum_{k=1}^{K} z_k^1 g_k^1 \geq g^1, & \\
& \sum_{k=1}^{K} z_k^1 x_k^1 \leq x_{k'}^1, & \\
& z_k^1 \geq 0, \ k = 1, \ldots, K, & \\
& \sum_{k=1}^{K} z_k^1 = 1, & \\
& \sum_{k=1}^{K} z_k^2 b_k^2 \geq b^2, & (P^2) \\
& \sum_{k'}^{K} z_k^2 c_k^2 = c^2, & \\
& \sum_{k=1}^{K} z_k^2 d_k^2 \geq d_{k'}^2, & \\
& \sum_{k=1}^{K} z_k^2 l_k^2 \leq l_{k'}^2, & \\
& \sum_{k=1}^{K} z_k^2 g_k^1 \leq g^1, & \\
& z_k^2 \geq 0, \ k = 1, \ldots, K, & \\
& \sum_{k=1}^{K} z_k^2 \leq 1, & \\
& b^2 \leq \delta g^1, & \\
& 1 \geq \delta > 0).
\end{aligned}$$

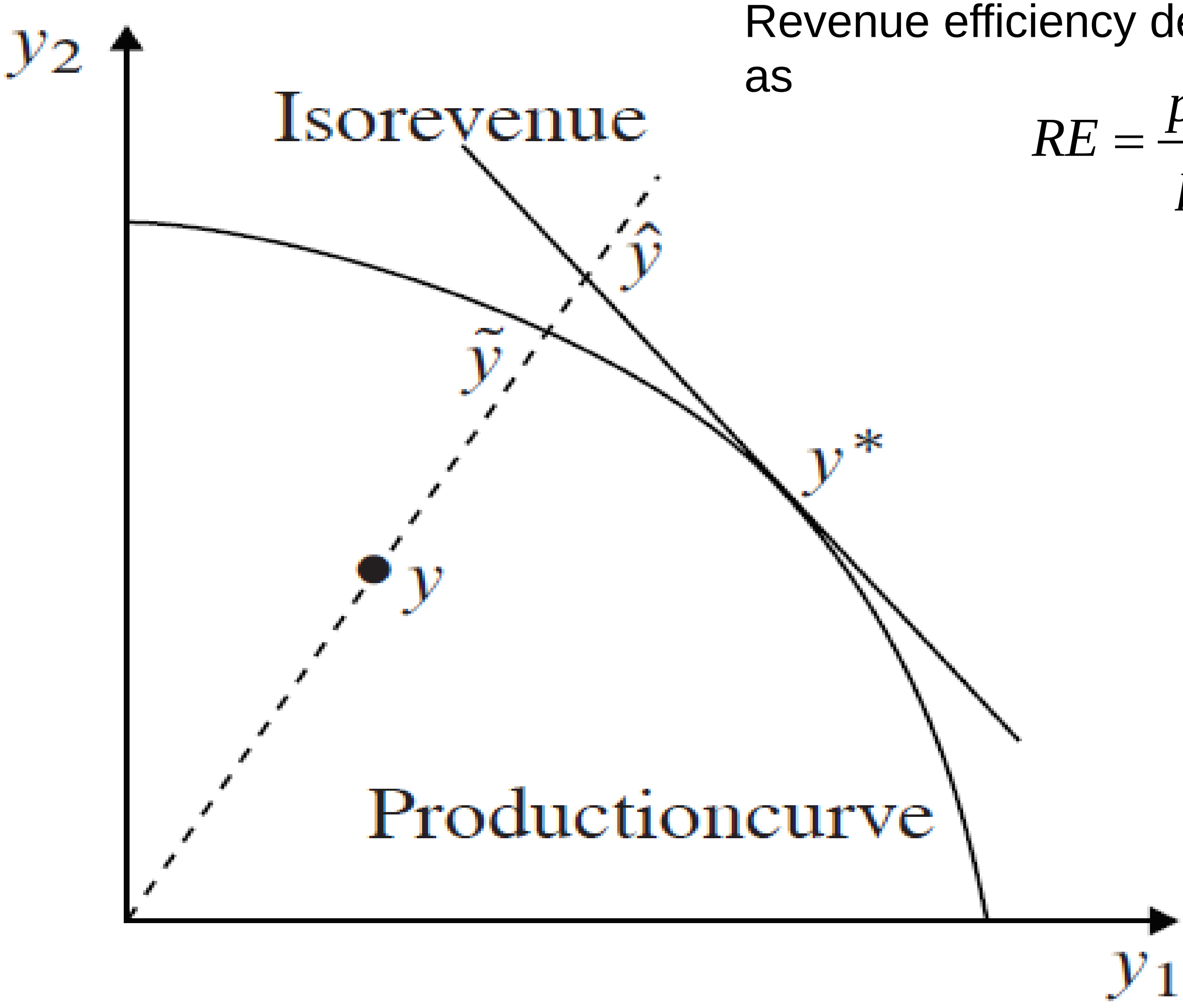
Technology 1

$$\begin{aligned}
P^1(x_{k'}^1) = \{(y^1, c^1, g^1) : \\
& \sum_{k=1}^{K} z_k^1 y_{km}^1 \geq y_m^1, \ m = 1, \ldots, M, \\
& \sum_{k'}^{K} z_k^1 c_k^1 = c^1, \\
& \sum_{k=1}^{K} z_k^1 g_k^1 \geq g_k^1, \\
& \sum_{k=1}^{K} z_k^1 x_k^1 \leq x_{k'}^1, \\
& z_k^1 \geq 0, \ k = 1, \ldots, K, \\
& \sum_{k=1}^{K} z_k^1 = 1 \}.
\end{aligned}$$

Technology 2

$$\begin{aligned}
P^2(l_{k'}^2, {}_1^2 g) = \{(b^2, c^2, d^2) : \\
& \sum_{k=1}^{K} z_k^2 b_k^2 \geq b^2, \\
& \sum_{k'}^{K} z_k^2 c_k^2 = c^2, \\
& \sum_{k=1}^{K} z_k^2 d_k^2 \geq d_{k'}^2, \\
& \sum_{k=1}^{K} z_k^2 l_k^2 \leq l_{k'}^2, \\
& \sum_{k=1}^{K} z_k^2 g_k^1 \leq g_k^1, \\
& z_k^2 \geq 0, \ k = 1, \ldots, K, \\
& \sum_{k=1}^{K} z_k^2 \leq 1, \\
& b^2 \leq \delta g_k^1 \}.
\end{aligned}$$

Efficiency measurement - illustration

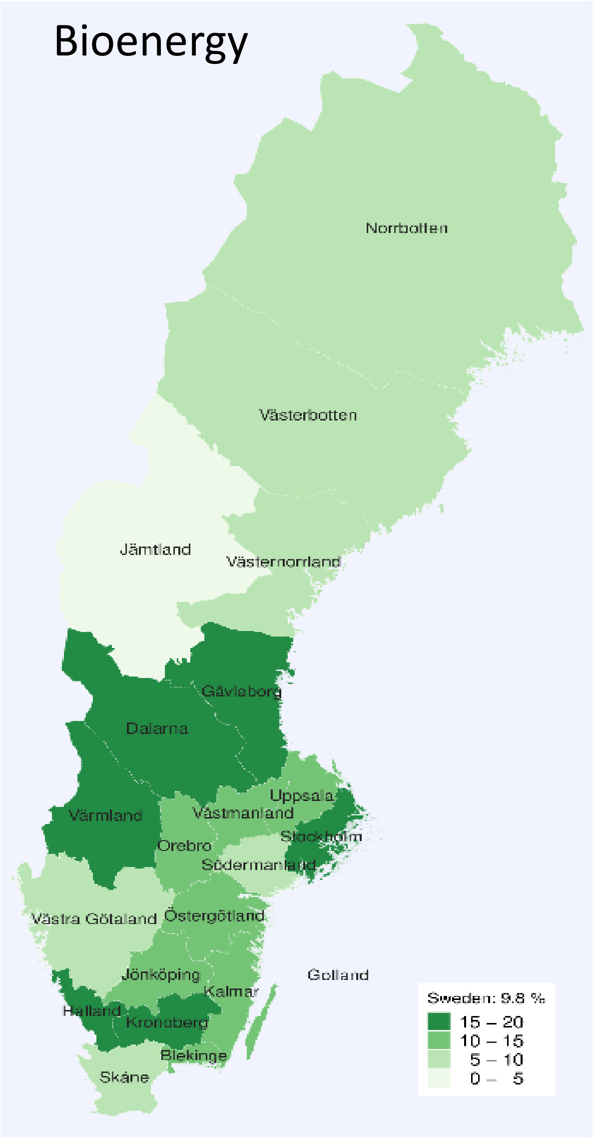


Revenue efficiency defined as

$$RE = \frac{py^*}{py}$$

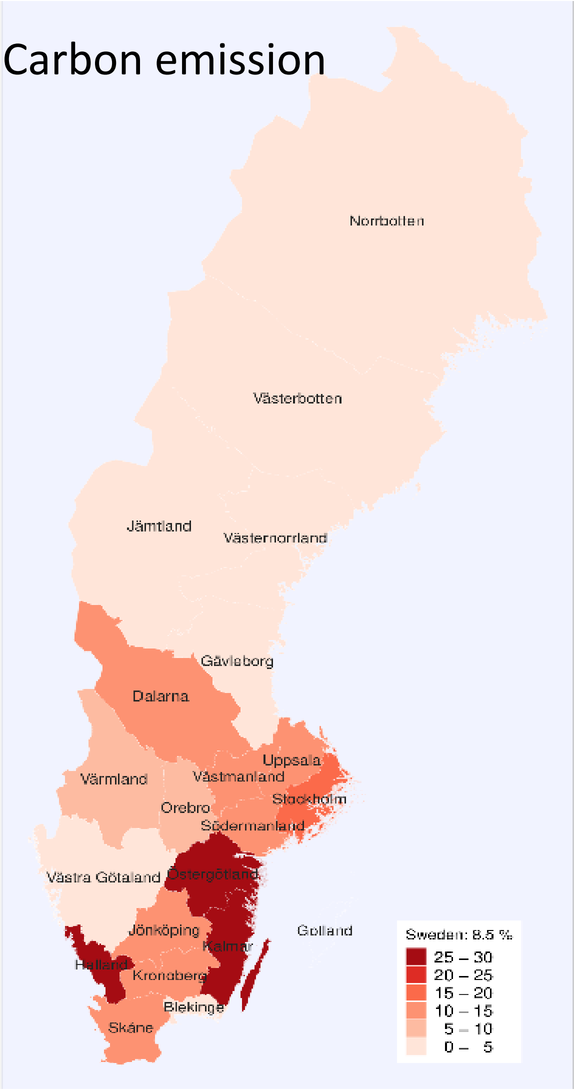
Main Results

Revenue efficiency and potential increasing in bioenergy production



Main Results

Potential change in carbon emission and deadwood



Eliminating inefficiencies – effects on prices

1. Based on mean price changes a more efficient forest management will generate larger price cuts in traditional forest products (sawmills/pulp) compared to energy sector. This will increase competition for these products as energy sector demand will increase.

2. A more effeicient forest management have little effect on products usually used by energy sector (bark/sawdust/dry chips), thus a more efficient forest management have quite small effect on prices that are important for the transformation to a more biobased energy system

3. The price effect from a more effcient forest use cannot fully offset the price effect of the energy sector expanding for use of forest biproducts. (Robert?)

Mean effect on forest product prices:

Sawlog	Pulpwood	Fuelwood	Harvesting residues	Woodchips	Dry chips	Sawdust	Bark
-19,8%	-25,8%	-4,1%	-4,0%	-25,8%	-4,4%	-2,8%	-3,7%

Working on

- Forest growth node in network (biophysical representation more realistic)
- Determinants of inefficiency in bioenergy production (2-stage DEA)
- Bi-level optimization application to effective forest climate policy – aligning forest owner incentives with regulator goals