Ecological Economics 107 (2014) 287–298

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Analysis

Modeling economic and carbon consequences of a shift to wood-based energy in a rural 'cluster'; a network analysis in southeast Alaska

David Saah [a], Trista Patterson [b], Thomas Buchholz [a,c,*], David Ganz [d], David Albert [e], Keith Rush [e]

[a] Spatial Informatics Group, LLC, 3248 Northampton Ct., Pleasanton, CA 94588, USA
[b] United States Department of Agriculture, Forest Service, 204 Siginaka Way, Sitka, AK, USA
[c] Gund Institute for Ecological Economics, University of Vermont, 617 Main Street, Burlington, VT 05405, USA
[d] Winrock International, Liberty Square, Suite 2002, 287 Silom Road, Bangrak, Bangkok 10500, Thailand
[e] The Nature Conservancy in Alaska, 416 Harris Street, Suite 301, Juneau, AK 99801, USA

ARTICLE INFO

Article history:
Received 20 February 2014
Received in revised form 7 July 2014
Accepted 8 August 2014
Available online 17 September 2014

Keywords:
Carbon accounting
Forest residue based biomass heating
Carbon lifecycle analysis
Carbon markets
Economic cluster analysis
Bioenergy

ABSTRACT

Integrated ecological and economic solutions are increasingly sought after by communities to provide basic energy needs such as home heating, transport, and electricity, while reducing drivers of and vulnerability to climate change. Small rural communities may require a coordinated approach to overcome the limitations of economies of scale. Low-carbon development strategies present potential for large payoffs at a household and community scale. Southeast Alaskan forests previously harvested for timber are currently re-growing and require thinning to maintain ecosystem service benefits such as wildlife habitat and hunting. Thinned material presents a potential biofuel source. However, without verification among decision alternatives, communities may not have the momentum, vision, or conviction to stimulate a shift to a new energy source. We present a network approach to evaluating multiple energy delivery pathways, and a calculation of carbon, energy, and dollar savings presented by each pathway. We quantify chain of production impacts; from the point of energy extraction and transport (upstream), through consumption and emission accounting (downstream). Our findings suggest substantial greenhouse gas emission savings of over 70% as well as heating cost savings for all bioenergy scenarios compared to fossil fuel scenarios. Outputs can facilitate dialog between land managers, planners, community members and decision-makers.

1. Energy Decisions in Peripheral Communities

Communities increasingly seek integrated ecological and economic solutions for basic energy needs such as home heating, transport and electricity, and reducing drivers of and vulnerability to climate change. For small or geographically isolated communities, high transportation costs, limited infrastructure, workforce and financial capital, all heighten the importance of coordination to overcome economies of scale. Few small communities have access to inventory tools and calculators, financial or technical wherewithal to compare among possible alternatives or configurations (Barthelmie et al., 2008; Pierce, 1996; Ridolfi et al., 2008; Smith, 1998). Quantification of costs and benefits, from economic, social and ecological perspectives, is a necessary first step to investment in solutions that take more local and global ecological and economic conditions into account.

2. Biomass as an Energy Alternative for Rural Clusters

Biomass from a wide diversity of sources (e.g. algae, agriculture, wood-based) presents many prospects for communities exploring alternatives to petroleum dependence. Wood-based biofuel alternatives are of interest, and plentiful in many forest-based rural communities from sources such as sawmill residues and second-growth forest. Biomass projects hold prospects for strengthening rural and local economies (Horne et al., 2007), reducing greenhouse gas emissions (GHG) and reducing foreign energy dependence (Perlack et al., 2005). Global (Hertwich and Peters, 2009) and multi-regional scale models (e.g. Korobeinikov et al., 2010) suggest that biomass products have economic and carbon benefits. However, quantified studies have yet to confirm that transition, opportunity and transaction costs as well as loss of associated ecosystem services (other than carbon sequestration) do not cancel out net benefits (Giarola et al., 2012, and Patrizi et al., 2013). For small, rural, or geographically isolated communities, small-scale wood-based bioenergy options may not be considered because the comparative analysis and case-by-case calculations can be expansive and complex (Barthelmie et al., 2008). Tools to facilitate and speed this process are needed to support a locally relevant, reliable, and well-examined energy strategy.

One strategy for overcoming the economy of scale issue often found in small rural communities is an economic cluster approach that capitalizes on 'the geographic concentration of interconnected companies, specialized suppliers, service providers, firms in related industries and associated institutions in particular fields that compete but that also

---

* Corresponding author. Tel.: +1 802 881 5590.
E-mail address: thomas.buchholz@uvm.edu (T. Buchholz).

http://dx.doi.org/10.1016/j.ecolecon.2014.08.011

cooperate' (Mitchell Group, 2003; Munnich et al., 2003; Porter, 1990; Wennberg and Lindqvist, 2010). In forest based rural communities this approach requires tighter coordination between members of the community, existing forest product producers, non-forest business, land owners, and land managers interested in developing cluster benefits (Rojas, 2007).

Beyond employment, the inclusion of biomass energy alternatives in land management has many motivations. Land managers must thus integrate new information and data sources on infrastructure, transport networks and local energy needs, and re-examine prior assumptions of joint-production (e.g. timber vs. biofuel vs. recreation vs. scenic impacts vs. wildlife habitats). General energy and production models for biofuels and timber have been developed at the global (e.g. Berndes et al., 2003), national (e.g. US Department of Energy, 2011), or multi-regional scale (e.g. Buchholz and Canham, 2011), with few applicable to small or finer scales.

Various tools have been used to account for community energy decisions, specifically lifecycle analysis (Zanchi et al., 2013), ecological footprint, energy analysis (e.g. Buchholz and Da Silva, 2010), and triple bottom line accounting (Rogers and Ryan, 2001). Yet, despite its impact from both economic and ecological perspectives, the transport leg of this analysis has often remained one of the least examined (Caro et al., 2014; Wei et al., 2014). Reasons for this include a paucity of data on fuel efficiency, use and terrain, difficulty of drawing a well-defined boundary to the system (Matthews et al., 2008), and because the responsibility for the resulting carbon is not formally assigned thus reducing the incentive to pursue the matter (Bastianoni et al., 2004).

This paper offers three specific contributions. First, we apply an approach defining clusters by geographic proximity, linked institutional commonalities and complementarities, and upstream (energy extraction and transport) and downstream (consumption and emission accounting) integration of the vertical chain of production on a landscape level.

Second, we take a network analysis approach to modeling carbon and local economic consequences of a shift from petroleum based sources to wood-based fuel in a relatively small, well-defined geographical area. The model presented calculates the carbon footprint from an actual biofuel source, at a micro-scale relevant to the cluster-based model. While prior efforts have developed more generalized models based on assumptions (Leighty et al., 2006a), our inputs are based on site-and-scale specific field data.

Third, the model platform presents a transparent calculation tool which can be used to alter inputs based on new data, parameters, assumptions and scenarios, or facilitate dialog between land managers, planners, and decision-makers. This tool is envisioned to improve the evaluation of scenarios and tradeoffs, address the challenge of constantly emerging data sets and alternatives, and decrease the difficulty modelers may have to articulate the uncertainty embedded in models involving consumption (Beynon and Munday, 2008).

Sustainable forest management, i.e. "the practice of meeting the forest resource needs and values of the present without compromising the similar capability of future generations" (Helms, 1998) can accommodate the principles of strong sustainability provided that stocks of natural capital are maintained (Pearce and Atkinson, 1993). The depletion of natural capital stock in this case, is not limited to trees but includes the sum of all forest-related assets, including the ecosystem services that a forest provides. In this article, we consider biomass fuel as a form of "natural income" (Costanza, 1996), and evaluate it against a petroleum based fuel in terms of GHG emissions, heat output, and dollar cost. Characterization of costs and benefits thus often focuses on balancing rates of wood extraction with rates of forest regeneration and self-thinning through density dependent mortality. Forest management, economics, and social perceptions are evaluated through various scenarios and tradeoffs involving fuelwood and/or biomass consumption, in addition to calculations of efforts to move harvested forests toward late-successional structures that store additional carbon in live trees (Hurteau and North, 2010).

3. Site Description

Southeastern Alaska (Fig. 1) is an area of steep, mountainous, coastal terrain, capped by ice fields and glaciers. A network of island and mainland communities are characterized by large distances, small populations, challenging topography and limited access to the continental road network — characteristics that define and constrain opportunities to derive profit and livelihood from resources. Transport costs are high for moving material around 700 miles each way from the nearest US port (Seattle). Machinery, fuel, and supplies are imported while seafood, timber, and minerals are exported.

At 17 million acres, the Tongass National Forest is the largest forest in the USDA Forest Service and the single largest intact store of temperate rain forest. Forest system carbon accounts for 8% of the conterminous USA and 0.25% of the carbon in global forest vegetation and soils (Leighty et al., 2006b). The interface between land and sea in the area creates one of the largest estuarine systems on the planet, with a productivity that supports regionally important stocks of salmon, as well as terrestrial and marine biodiversity. Productive forest land, rare large-tree forests and karst regions are of international significance for their intensity, diversity and recreational values, as well as biological, cultural and paleontological values (Baichtal and Swanston 1996, Beier et al., 2008).

Prince of Wales (POW) Island is the largest island in the Alexander Archipelago (Fig. 2) and ranks highly for ecological values in the region (Beier et al., 2008). Karst and large-tree forests are of international significance for their productivity, diversity and recreational values, as well as biological, cultural and paleontological values (Baichtal and Swanston, 1996).

4. Background on Second-growth and Thinning

Timber extraction of Sitka spruce or western Hemlock has been an important driver of changes to Southeast Alaskan economies and landscapes alike. Intensive clear cutting accompanied the establishment of pulp mills in the region, particularly starting in 1954 with the granting of two 50-year timber contracts to large pulp mills until 1997 with the closing of the last pulp mill and a net loss to the Tongass timber program (Leighty et al., 2006b). Smaller mills in the area remain, however much of the higher grade, easier access timber has already been removed. The land use history of the area has strongly influenced the trajectory of forest re-growth on the minor portion of the landscape that was harvested. 'Second growth' or 'Young growth' are terms used to describe the 100 years following a clear-cut event, during which seedlings compete for light and nutrients, eventually forming a dense re-growth thicket and canopy (Alaback, 1982a,b, 1984; Deal, 2001; Deal et al., 1991; Hennon and McClellan, 2003) which prevents sunlight from reaching the forest floor, reduces wildlife density (Dellasala et al., 1996; Hanley, 1993; Schoen et al., 1981, 1988; Wallmo and Schoen, 1980), and excludes understory vegetation almost to exclusion (Oliver, 1981; Alaback, 1982a; Deal et al., 1991; Alaback, 1982b, 1984; Tappeiner and Alaback, 1989 as summarized in Deal and Tappeiner, 2002).

Despite an initial 10–15 years of rapid forest regrowth that is conducive to many hunted populations such as black-tailed deer, and bear, the 'young-growth' then enters a second phase called 'stem exclusion', where the new trees grow in so densely that the canopy closes out light entirely, slowing growth and resulting in declines in plant diversity, and reduced forage for wildlife (Hanley et al., 2013). Restoration of these land areas has been proposed, i.e. to thin young stands to allow for passage of wildlife and hunters, increase biodiversity, and provide a source of fuel for firewood and biomass projects.

Thinning is a means of coping with the dense forest re-growth. "Second-growth thinning" has been shown to improve conditions for

Fig. 1. Map of Southeast Alaska region. Prince of Wales (POW) Island exhibits a typical topography for the whole region.

Fig. 2. Map of Prince of Wales Island communities.

recreators, hunters, and wildlife, allows more sunlight to the forest floor (which promotes biodiversity and wildlife forage), and alters the carbon storage trajectory in remaining live trees (Hurteau and North, 2010). Thinning, or 'partial cutting' on formerly clear-cut lands ideally takes place once the crowns of the regenerating stand make contact with adjacent crowns which takes place at 10 to 15 years of stand age in Southeastern Alaska. Thinning has increased management options for desired forest characteristics (Alaback, 2010; Barbour et al., 2005; Deal et al., 2002; McClellan et al., 2000; Peterson and Monserud, 2002) by simulating old-growth structural diversity and increase species diversity among understory plants (Deal, 1999, 2001; Deal and Tappeiner, 2002; Deal et al., 2003; Hanley, 2005; Zaborske et al., 2002), which can result in increases of small mammals (Hanley, 1996; Hanley and Barnard, 1999a,b) and other species (see review in Deal, 2007). The increased understory has been seen to increase the abundance of wildlife such as black-tailed deer (Wallmo and Schoen, 1980; Schoen et al., 1988), and can improve access for recreation, gathering of non-timber forest products and hunting.

There have been several efforts made to develop models that help in prioritizing watersheds on POW Island in terms of the diversity of ecosystem goods and services they provide (Albert and Schoen, 2007), their overall biological productivity, use, and risk of disturbance they are exposed to (Beier et al., 2008). Many ecosystem service benefits may result from active management of formerly harvested timber stands (Hanley et al., 2013). Pre-commercial thinning (i.e. cutting some trees and reducing the intra-tree competition for light, space, and nutrients) results in more vigorous, resilient stands that grow faster, and ideally sequesters more carbon (Oliver and Larson, 1996, McClellan, 2008; Lowell et al., 2008). Thinned stands may also provide more browse for deer populations, and allow easier access to hunters (Hanley et al., 2013). Young-growth timber thinning may provide jobs in the thinning, transport, and processing into a number of products such as fire wood and pellets (Alexander et al., 2010; Beck Group, 2009).

That said, the net impact in terms of carbon flux and wildlife habitat alike, is greatly dependent on the life cycle of thinned and harvested products. For example, slash may inhibit the passage of wildlife and humans if not removed from the site. Yet removal, or on-site burning, may cause additional impact and/or GHG emissions. The net sequestration rate of the stand depends on the particulars of the stand age; the past and future harvest date, and site productivity before and after thinning. Documentation of a net carbon benefit must also assure that the net emissions from the harvest act itself do not outweigh the increased sequestration rate that results.

Though young growth volume could be available in the 2010s, economically sustainable young growth forest management is not estimated to be possible until the early 2030s (Alexander et al., 2010). Yet the additional ecosystem service benefits from thinning are seen as socially and ecologically desirable, and when considered in net ecological economic analysis, may prove to tip the balance in favor of thinning activity.

The life cycle fate of harvested forest products may also affect the potential net carbon benefits of a thinning activity. Furthermore, petroleum and transport costs are predominant factors in the economic and commercial functioning in Southeast Alaska. Comparatively high fossil fuel costs represent a substantial risk and comparative disadvantage for entrepreneurs seeking opportunities in the area. A full-scale forest restoration program on POW Island, in theory, could address watershed health and provide a new source of economic benefit to formerly extractive timber dependent communities. Yet integrated planning that addresses biomass sourced fuel, the ecosystem service benefits from thinning, and the jobs created from the thinning and processing of the harvested material must also address the other substantial factors: geography and a limited as well as particular transport network. Feasibility assessments need to involve close partnership among the US Forest Service, local industry, environmental groups, and local communities, and will require transparent tools which assist in the analysis of the costs and benefits of various fuel sources, distribution pathways, and procurement strategies.

5. Approach

Our assessment is structured using an economic cluster approach defined by a dense network of resources, companies and institutions in a given geographic sphere. The cluster is composed of production companies, raw material suppliers, service providers, and public institutions such as logging, conservation, and energy production (Porter, 1990). The cluster typically contains three types of connections: (1) Vertical — a connection between provider and manufacturer along the production line; (2) Horizontal — a connection between manufacturers of complementary products; and (3) Institutional — a connection between companies and public institutions (Porter, 1990). These connections facilitate resource-use and cost-efficiencies, and when studying distributed energy systems, typically only take into account hard infrastructure utilization (e.g. Leighty et al., 2006a). In this study, we are taking into account natural resource availability into the distributed resource concept and using that as an input into what would be considered an energy cluster. Using this framework two issues will become prioritized: fuels sources and energy production should be created as close to the end users as possible; and energy feed stock demands will be integrated with equally weighted other demands such as improved habitat quality (through structurally heterogeneous thinning). This approach allows for the increased use of a constrained resource while considering area- and usage-specific obligations and restrictions. In this case, energy would not be used just as a demand, but energy would be also used as an aid to natural resource conservation.

5.1. Life Cycle Carbon Calculators

Carbon calculators analyzing the life cycle emissions of a given activity, product, or fuel have been increasingly relied upon to describe evaluative frameworks, and improve consistency and effectiveness in communication (Kim and Neff, 2009). Yet frequently, the underlying data and assumptions, the tradeoffs, and the comparisons among multiple outcomes are not particularly transparent. Carbon calculators generally define the scope of the studied comparison (in space and time), and describe the life cycle of the product (from source to end destination), the available data inputs and data ranges, and the factors which will describe the outputs of the compared scenario, product, or technique. As the model used in this study is offered as a calculator, the appendices offer access to the modeling tool (Appendix B), as well as information about which inputs may be manipulated in order to create other scenarios or compare among other conditions. Clear, specific, and transparent methods and scope in calculators can assist informational exchange, scenario exploration, and decision support between developers, managers, private, public, and tribal entities (Kim and Neff, 2009). The emission LCA applied in this study included CO_2, CH_4, and N_2O emissions in the short- and long-haul transportation of heating oil from Seattle and of biomass off the logging site respectively, through to the delivery to a final consumer (Fig. 3).

5.2. Methods

Biomass life cycle assessments are becoming more standardized as a result of their increased use in measuring potential environmental, social and economic impacts of biofuels. Traditional life cycle analysis is conducted in two phases standardized by the International Organization for Standardization (ISO 14040 and ISO 14044, ISO, 2006), an approach we truncated according to our assumption that the fuel type chosen on POW Island would not influence the rate of extraction, refining, and transport of petroleum to Seattle which is considered as a business as usual scenario. To maintain focus on the 'additionality' offered by biofuel utilization, the life cycle analysis system boundary begins with fuels originating either in Seattle (petroleum scenarios), or the study site (POW Island forest area — biofuel options) and ends with combustion of the fuels for heat generation. The life cycle stages included in the system boundary are harvesting, biomass chip transport, biomass processing, and converting it into community based heat/emissions for residential homes and centralized facilities. Fuel demands are estimated for POW Island communities in Point Baker, Port Protection, Whale Pass, Edna Bay, Coffman Cove, Naukati Bay, Klawock, Thorne Bay, Craig, Hollis, Kasaan, and Hydaburg (Fig. 2).

The environmental impacts were assessed using five principal inputs: (1) landscape characterization and scenario design for biomass extraction on second growth stands, (2) characterization of forest operations and equipment configurations for extracting biomass in second

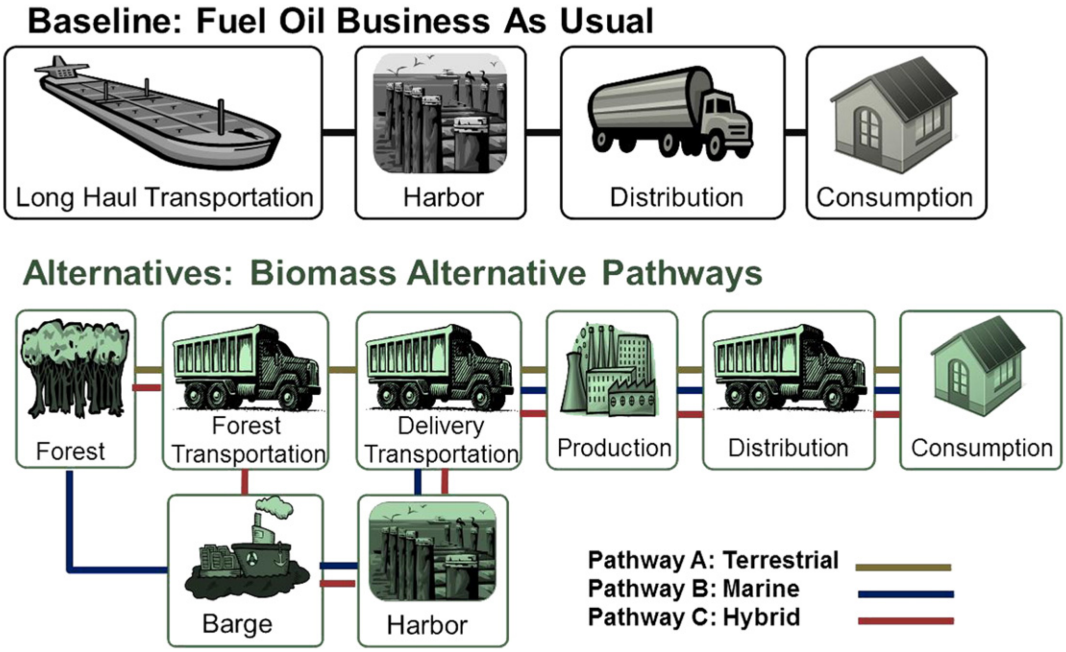


Fig. 3. Spatial segmentation illustration for POW: There are three pathways; A) Forest → Transport → Production → Distribution → End Use; B) Forest → Marine → Harbor → Transport → Production → Distribution → End Use; and C) Forest → Transport → Marine → Harbor → Transport → Production → Distribution → End Use.

growth stands, (3) transportation network systems via road-ways and maritime routes, (4) central processing at one of three proposed locations on POW Island, and (5) heat production efficiencies comparing woody biomass to traditional heating oil. Associated pathway assumptions are documented in Appendix (A).

The analysis considers multiple source and transport vectors, and multiple heat efficiency, biomass yields, and fuel prices by performing a network analysis and dynamic variation of input parameters, in order to form the highest and lowest values possible for each scenario estimate.

5.3. Baseline

We first defined a baseline scenario using the 2008 energy demand data for communities and transportation on POW Island based on local household level data. The baseline assumes that existing heating is 100% heating oil based. A transportation network analysis was utilized to quantify GHG emissions, heat utilization and cost associated with heating oil utilization in the business as usual baseline. Infrastructure retrofits, and disposal of old heating infrastructure, capital and operational cost of equipment and personnel are not included in either baseline or alternative scenarios.

5.3.1 . Demand

Community heating estimates assumed fuel type (heating oil #2), an average oil usage of 40.6 l/m^2/year, an average heating technology efficiency of 78%, a higher heating value of 10.8 kWh/l, and GHG emissions at 3.14 kg of CO_2 equivalents per liter. Biomass demand on a per m^2/year basis was synchronized to the net energy demand for heating oil systems based on a biomass heating technology efficiency of 80% for new systems, and a higher heating value of 5820 MWh/Mg. The total footprint per community was based on energy demand estimates for home heating (a function of number of houses, average size, and occupancy rate). Heat for public and community shared buildings was estimated to be one half of the total housing footprint (see Appendix B).

5.3.2. Long Haul Transportation

Transportation energy estimates were based on two segments, the long haul emissions resulting from transporting petroleum based fuel from the refinery to POW Island, and the short haul emissions resulting from transporting the fuel from the harbor to local communities. Long haul estimates were based on round trip ship capacity, and estimates of fuel consumption based on average distance, speed, energy efficiency and daily fuel consumption rate (see Appendix B).

5.3.3. Short Haul Transportation

Short haul travel involved estimates of fuel consumption, heat utilization, and GHG estimates resulting from transporting fuel from the harbor to local communities via the POW road system. Round trips were based on assumptions of an empty return, tanker truck capacity, and community energy demand rounded to the nearest full trip. Fuel consumption was based on road distance, speed, mass transported, and estimates of fuel efficiency (CCAR, 2009; Fig. 4). GHG emissions were based on total fuel utilization and GHG emission factors (CCAR, 2009).

5.3.4. Total Baseline Estimate

Baselines were estimated for GHG emissions, heat usage, and costs. GHG and heat usage are the sum from baseline energy demand, as well as from long and short haul travel. Total baseline cost measures were estimated based on fuel consumption and do not include the capital or operational cost of the equipment or personnel used.

5.4. Alternative Biomass Scenarios

The alternative biomass scenarios are based on estimates of large volumes of slash and un-merchantable timber resulting from forest thinning treatments, and for which geo-spatial profiles of the land acreage, feedstock, moisture and heat content for transport are already well documented (TNC Alaska, 2013). Currently this material is left to decompose or is burnt on site. Transport pathways utilize existing path possibilities as established by current restoration efforts. Biomass supply sites are accessible from land (terrestrial extraction), marine and shoreline sites (marine extraction), and a hybrid of the two. Transport distance alternatives were then calculated to account for location, access to existing infrastructure, and community needs (Control Lake cross roads, Craig sorting yard, Thorne Bay sorting yard). The energy demand for biomass was normalized to baseline community estimates

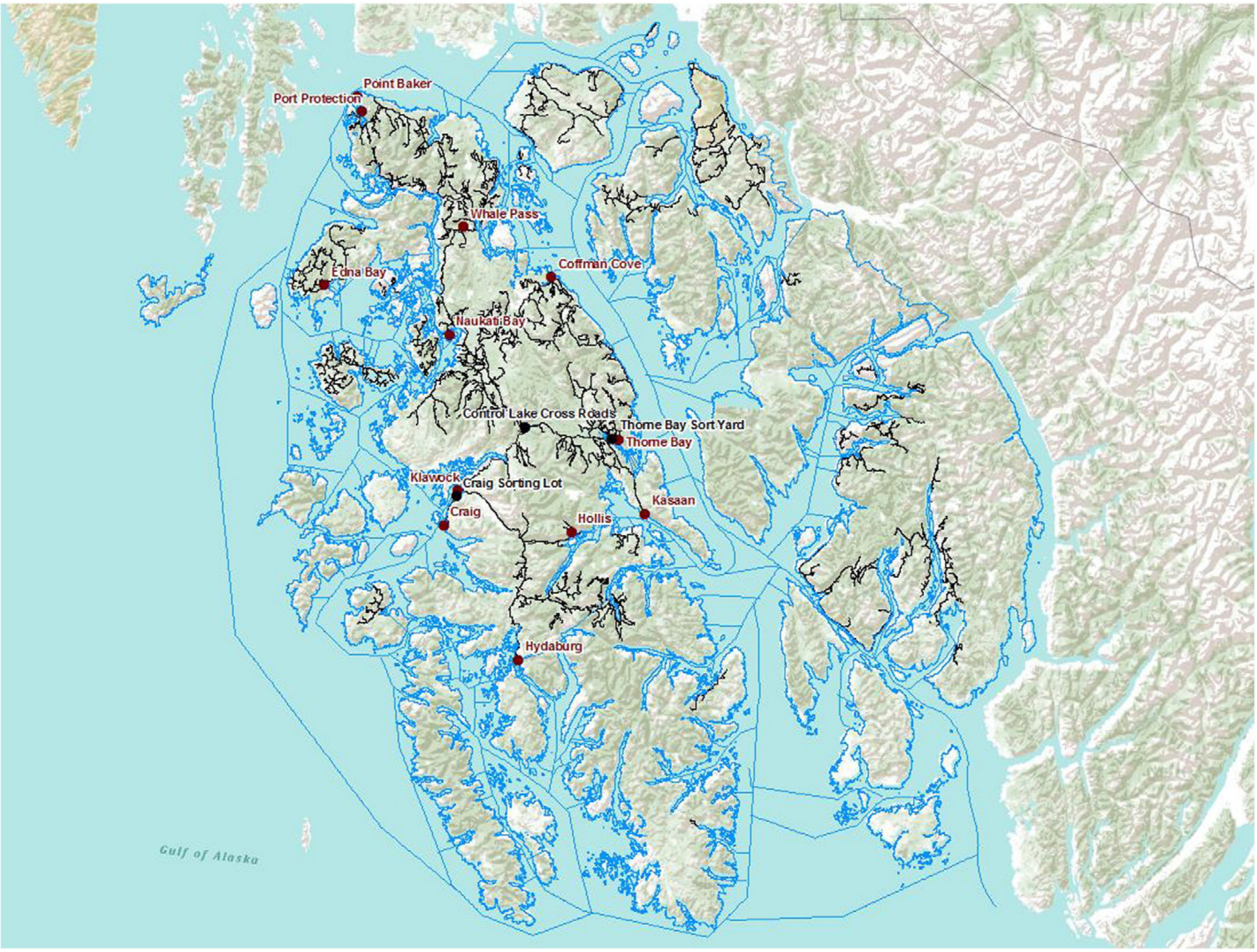


Fig. 4. Map of POW communities and terrestrial transport network.

(Fig. 5). For example, the heat demand was established by the heating oil simulation and the biomass system was normalized to deliver the same amount of heat to the end user.

A transportation network analysis was utilized to quantify GHG emissions, heat utilization and cost associated with three separate pathways associated with the alternative scenarios.

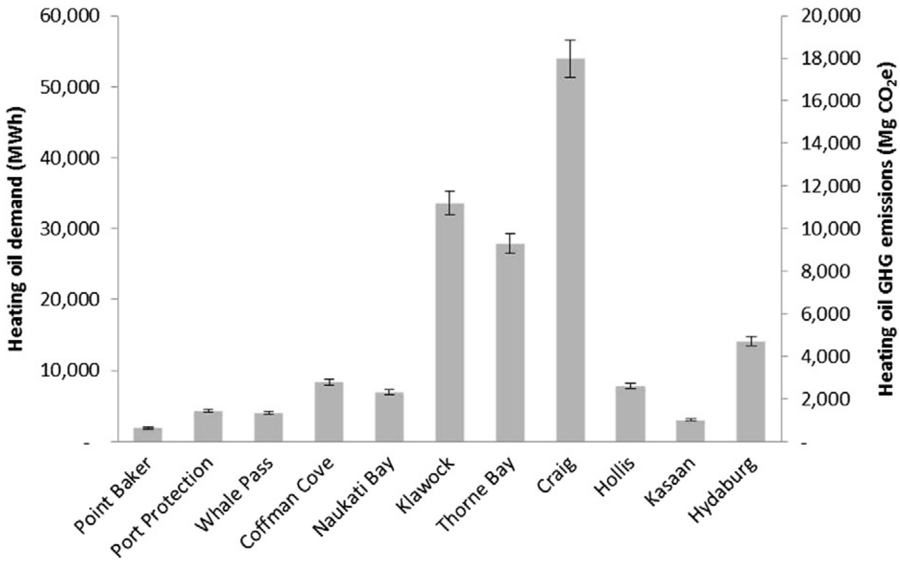


Fig. 5. POW Island heating oil demand, by community (error bars: ±10%). Differences between communities can be largely explained by a difference in population size. Total GHG emissions equaled 56,406 Mg CO_2e.

The three alternative pathways involved distinct fuel use and emission profiles for each segment of the biomass extraction and transport process (Fig. 3). The terrestrial pathway contains the following segments in order; forest biomass, forest transportation to the landing, delivery transportation to the facility, conversion of biomass at the facility, distribution to the end user, and consumption by the end user. The marine pathway contains the following segments in order; forest biomass, transportation to the barge, delivery transportation from barge to the harbor, delivery transportation from the harbor to the facility, production of biomass at the facility, distribution to the end user, and consumption by the end user. The hybrid pathway contains the following segments in order; forest biomass, forest transportation to the barge transfer location, transportation to the barge, delivery transportation from barge to the harbor, delivery transportation from harbor to the facility, production of biomass at the facility, distribution to the end user, and consumption by the end user. The total GHG emissions and energy demand for each pathway are estimated by summing the values from each of the segments then averaging and normalizing it by the total demand identified in the baseline analysis.

5.5. Analytics

One challenge to life cycle analysis is accounting for multiple factors that can vary with and against each other, which shift project-specific cumulative impacts. Our analytical framework captures the possible variation stemming from the use of any of three transport pathways, three transfer site locations, and various possible fuel efficiencies. Eighty-one simulations were completed, with results capturing a full matrix sensitivity analysis of High (+10%), Average, and Low (−10%) fuel efficiencies. The assumptions used for each of the segments were held constant (complete listing see Fig. 6).

5.6. Potential Emission Offsets

GHG emission savings derived from a switch of fossil fuel based heating systems to biomass based heating systems might potentially be eligible for participation in the voluntary emission offset market. In order to gage the potential eligibility as well as revenues from selling carbon offsets, we identified potentially applicable protocols under the Clean Development Mechanism (CDM) of the United Nation Framework Convention on Climate Change (UNFCCC) guidelines and quantified emissions as well as income. The rationale behind the choice of CDM UNFCCC protocols is a likely endorsement of these frameworks by voluntary (e.g. American Carbon Registry) carbon markets. We analyzed two protocols, a simplified small-scale as well as a large-scale methodology, for applicability and quantification of carbon credits, namely the small-scale methodology 'AMS I.E. Switch from non-renewable biomass for thermal applications by the user' (CDM UNFCCC, 2013a) with a simplified framework to accommodate resource limitations of small-scale projects and 'AM0036: Fuel switch from fossil fuels to biomass residues in heat generation equipment Version 04.0.0' (CDM UNFCCC, 2013b) applicable to larger projects.

6. Results

The results were divided into three sections consistent with the research objectives namely quantifying the cluster of biomass utilization on GHGs, heat utilization, and overall cost compared to heating oil as a heating source. Results are presented for each of the major pathways by production yard integrating the sensitivity analysis.

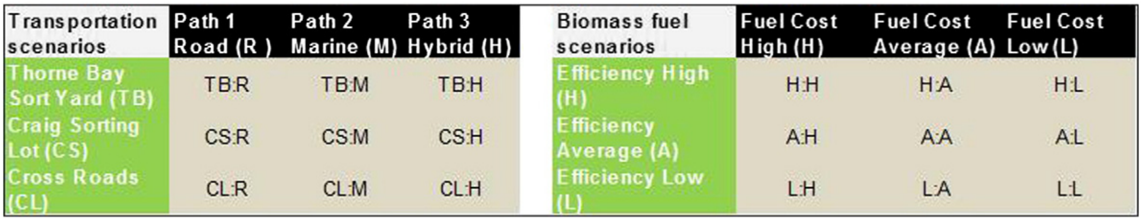
6.1. Diverted Greenhouse Gas Emissions

We found substantial GHG emission savings for all scenarios when comparing biomass utilization to fossil fuels (Fig. 7). Each biomass scenario provided substantial GHG emission savings and the differences in emission savings range by less than 15% in emission reduction potential independent of pathway or biomass yard. These substantial GHG emission savings are a result of reduced transportation emissions due to shorter transport distances for biomass compared to heating oil as well as the assumption that GHG stack emissions are zeroed out in the case of biomass under a bioenergy scenario since these emissions would be anyway emissions occurring at the forest if residues would have been left to decay.

6.2. Heat Cost Savings

At a delivered pellet price of 331 US$/Mg and a heating oil price of 1.16 US$/l, the heat cost savings range from 15 to 19 US$/m^2/year (Fig. 8). Savings depending on technical efficiencies and community locations could be realized by conversion to biomass fuel sources. This is equivalent to about 2500 to 3200 US$ in potential annual savings for the average household of 167 m^2. Assuming costs of 10,000 US$ for the installation of a wood pellet system for the average household, the payback for this capital investment would be less than four years. Further assuming that a wood pellet industry develops on POW fed by local forest thinnings, most of the expenses on fuel would now circulate through the community rather than leaving the locality. Instead of a total of ~$16,000 spent on the terrestrial delivery of heating oil annually — the only source of local income from home heating besides oil storage and furnace upkeep under current conditions, the bioenergy scenario would circulate over $6.5 million annually through the community. While a fraction of this sum would also service capital costs on infrastructure and leave the island (pellet mill technology, transportation equipment, etc.), the magnitude of the difference between the two scenarios cancels out any doubt of the socio-economic boost awaiting the community.

It should be noted that these savings do not reflect the cost of conversion, maintenance, or other costs associated with transport infrastructure, transaction costs, or various other start-up costs associated with biomass fuel production. We calculated a total biomass demand of 31,371 Mg biomass if all residential and communal buildings would be converted to wood-based heat. At a pellet price of 331 US$/Mg, this conversion would create an industry with annual revenues of 10,383,801 US$ which could offset initial infrastructure costs. While these estimated values omit the general volatility of fuel prices, we included a general sensitivity based on average fuel prices. Changing heating oil prices by ± 10% did not result in significant changes to heating cost savings.



Transportation scenarios	Path 1 Road (R)	Path 2 Marine (M)	Path 3 Hybrid (H)
Thorne Bay Sort Yard (TB)	TB:R	TB:M	TB:H
Craig Sorting Lot (CS)	CS:R	CS:M	CS:H
Cross Roads (CL)	CL:R	CL:M	CL:H

Biomass fuel scenarios	Fuel Cost High (H)	Fuel Cost Average (A)	Fuel Cost Low (L)
Efficiency High (H)	H:H	H:A	H:L
Efficiency Average (A)	A:H	A:A	A:L
Efficiency Low (L)	L:H	L:A	L:L

Fig. 6. Transportation, biomass sorting yard, and cost scenario assumptions.

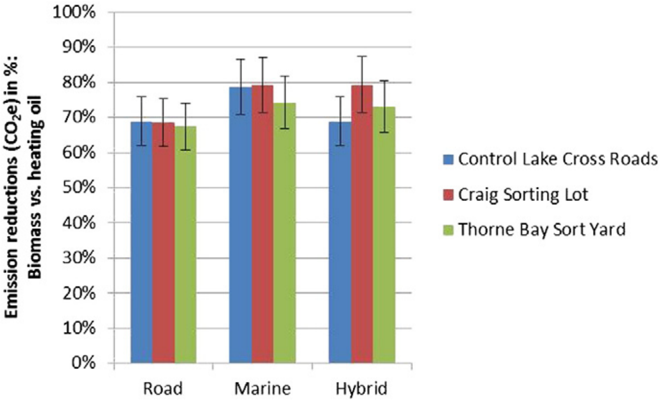


Fig. 7. Detailed scenario results: Comparison of GHG emission savings from the current level (56,406 Mg CO_2e; see Fig. 5) among alternative pathways resulting from a switch from heating oil to wood for each of the nine analyzed procurement scenarios. Despite large variances in transport pathways and distances, GHG emission savings are comparable across all analyzed procurement scenarios.

If we assume that the distribution costs are the same, we're internalizing the biofuel production costs into the delivered biofuel's price. Looking at the differential between the heating potential between the two fuel sources is therefore an estimate of the savings from a fuel switch to the end users. In terms of the total lifecycle, there are savings anticipated from carbon dioxide emissions and dollar savings, regardless of transport route.

6.3. Emission Offsets and Revenues Based on CDM UNFCC Methodologies

Both methodologies reviewed, the simplified small-scale as well as the large-scale methodology, could be potentially applicable to a fuel switch project based on the biomass origin, namely harvest residues. As long as regional laws are complied with, the simplified small-scale methodology accommodates biomass as long as it is derived from “land area remains a forest” or as long as “[…] practices are undertaken on these land areas to ensure, in particular, that the level of carbon stocks on these land areas does not systematically decrease over time (carbon stocks may temporarily decrease due to harvesting)” (CDM UNFCCC, 2013a). In contrast, the large-scale methodology is restricted to biomass residues, i.e. biomass of non-marketable quality that occurs during logging operations or at a processing facility (CDM UNFCCC, 2013a). While for the simplified small-scale methodology only stack CO_2 emissions for the fossil fuel baseline have to be quantified and can be marketed as offsets in their entirety, the large-scale methodology requires an accounting of CO_2 emissions during the processing and transportation of the biomass as well. Project activity emissions must include CO_2 emissions associated with “off-site transportation of biomass residues” and “on-site fossil fuel and electricity consumption due to the project activity”. Emissions originating in harvest activities as well as the combustion of biomass are excluded as “it is assumed that CO_2 emissions from surplus biomass do not lead to changes of carbon pools in the LULUCF sector”. Accounting for CH_4 emissions during a potential decay of the biomass under a business as usual scenario is optional as long as CH_4 emissions during a biomass combustion process under the project activity scenario are also considered.

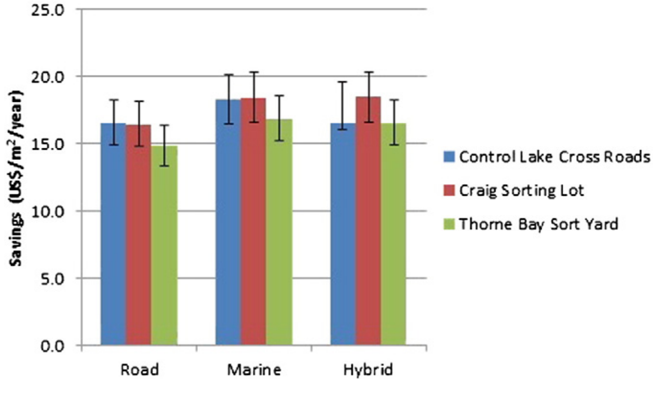


Fig. 8. Heat cost savings for each of the nine analyzed procurement scenarios (error bars: ± 10%). Dollar savings could be used to relieve cost of shifting public or household infrastructure over to enable biomass as a fuel source. Despite large variances in transport pathways and distances, heating cost savings are comparable across all analyzed procurement scenarios.

Using the large-scale methodology, marketable emission reductions compared to a baseline are substantial. Depending on the pathway and sorting yard chosen, CO_2 emissions would be cut by around 75–80% (Table 1). Emission savings differed compared to results presented above as transport and processing emissions for a fossil fuel baseline are not included in the ACM0036 accounting. If excluding CH_4 emissions and up to over 150% if also considering CH_4 emissions from biomass decay compared to fossil fuel emissions only under a fossil fuel baseline. Total net income would range from 61 to 127 US$ per household and year depending on the inclusion or exclusion of CH_4 and the choice of the methodology.

Potential eligibility of this project under small-scale methodologies potentially depends on the combined capacity of the installed equipment which is at around 50 MW for the project considered here. While other small-scale CDM UNFCCC offset methodologies are specific about cut-off capacities (e.g. 45 MW under the simplified small-scale methodology; CDM UNFCCC, 2013c). Another critical consideration for application of the CDM UNFCCC protocols is the expected lifetime of the installed (biomass-combustion) equipment. While small-scale methodologies are not specific about the total length of a project lifetime and therefore the period under which payments are eligible, the large-scale methodology specifies that a project lifetime is limited to the life expectancy of the currently installed equipment. This expected lifetime is substantially shorter for residential heating equipment (~15 years) than for commercial applications, thus putting an offset project based on residential heating applications at a considerable disadvantage compared to commercial-scale combustion equipment with life expectancies in the range of 30 years (CDM UNFCCC, 2013d).

7. Discussion

Addressing climate change vulnerability and the drivers of climate change requires radical rethinking of many structures and processes, and implemented changes that require coordination among many actors and systems simultaneously. Sometimes, an attractive solution may not be seriously considered, either because it goes against the mindset of how things are generally ‘done’, or it requires new social and built infrastructure, or the full range of costs and benefits (economic, social, and environmental) have not been fully explored. A certain approach may remain in place, even when more desirable alternatives, and the technology to implement them, are available (Costanza, 1996). For example, the American transport system remains rigidly tied to petroleum extraction, refining, transport and distribution, even when electric cars offer alternatives, in part because re-tooling for electricity distribution requires coordination, cost, and perhaps unintended consequences.

The tendency is to think that bigger is better for energy systems. For geographically isolated communities this is not often the case, because scaling up results in transport costs that absorb the efficiency gains. However, because we included the environmental cost of shipping fuels into the equation the cost-efficiency gains through economies of scale (but coupled with increased transport distances) may cancel out.

Yet while acknowledging the extreme difficulty of whole-system conversion, and the risks to various service and product entrepreneurs, we must also acknowledge that few biomass projects and products pencil out to what the results of this study show to be extremely promising

Table 1
Emission reduction and revenue projections from emission offset markets.

Baseline fossil fuel emissions (Mg CO_2e)					55,349			
Emission savings and revenues	Excluding CH_4 emissions				Including CH_4 emissions[a]			
	Total emission savings		Total net income[b]	Net income per household	Total emission savings		Total net income[b]	Net income per household
	(Mg CO_2e)	% of baseline	(US$/year)	(US$/year)	(Mg CO_2e)	% of baseline	(US$/year)	(US$/year)
ACM 0036 (large scale methodology)	40,570–46,341	73%–84%	161,619–185,973	61–70	77,825–83,913	141%–152%	311,300–335,654	118–127
AMS I.C. (simplified small-scale methodology)	55,349	100%	221,396	84	N/A	N/A	N/A	N/A

[a] Assuming 10% and 0.021% of carbon are emitted as CH_4 during biomass decay and combustion, respectively (Mann and Spath, 2001; United States Environmental Protection Agency, 2008); 2% soil mineralization rate of carbon when biomass decays and 1% of carbon are permanently sequestered in ash in case of combustion.

[b] Assuming a project overhead cost averaging 20% of total revenues.

in favor of biomass. Even considered conservative estimates, these numbers have been reinforced by numerous anecdotal data, and affirmations from sources throughout Southeast Alaska and other geographies. Thus, while the community risks might incline us to suggest that these systems are not as capable of producing positive results than we have reported, we must perhaps instead provide the caveat that we have — even while reporting this system in extremely positive light, grossly underestimated the net benefits.

For example, the heating energy network and systems that are currently in place in POW and elsewhere are (in part) an artifact of historical demands and practices. These artifacts are difficult to change in the best case scenarios. Even if an attractive alternative presents itself, we are often ambivalent for a lack of clarity about the production chain, the infrastructure, the costs and the benefits in quantified and predictable form. Social conversion incurs investment, and uncertainty and mistakes can come with high social costs to communities. Broad scale, integrated change is often rare. Pioneers are few, and often uncoordinated with other elements of the value chain, and economies of scale in small rural environs often don't scale up because covering broader territory incurs transportation costs that may cancel out benefits. These limitations have often stunted the growth of biomass programs due to three major reasons; misalignment of the demand and production scales, lack of understanding of the needed social capital, and failure to optimize for energy type (thermal vs. electric).

There are several caveats that need to be stated and clarified. LCAs have been used to clarify many complicated issues, given that there are several limitations associated with the approach used in this analysis. Listed below are several caveats both quantitative and qualitative.

7.1. Caveats-LCA

The boundary of analysis between the fossil fuel business as usual (BAU) and biomass alternatives was not the same, because the fossil fuel BAU did not include the costs or emissions associated with exploration, extraction, transportation of crude oil to a refinery, or processing of heating oil prior to shipment of the product from Seattle to POW. We assumed that for this analysis, this portion of the BAU would have continued independent of implementing a community based biomass program. The results presented here are therefore conservative in terms of the associated GHG benefits derived from a fuel switch from fossil fuels to biomass.

7.2. Caveats-ecological

Even when biomass utilization is part of an ecological restoration plan, quantified ecological benefits are still not well understood. The long-term, energetic, and landscape level ecological impacts of thinning are still in the early phases of study (Hanley et al., 2013). The thinning of dense second growth vegetation in forest stands has been proposed to contribute to forest structure attributes which benefit species diversity, however study results are not unequivocal and ultimately depend on the long-term fate of the forest stand.

The geo-spatial data estimates of biomass productivity used in this study generalize and simplify what is in reality a mosaic of rock, ice, alpine, muskeg bog, avalanche slopes, scrub forest, and productive forest lands. Current models used to estimate sustained yield have proven successful for traditional harvesting techniques in the area. An impact from biomass restoration efforts on forest productivity is less well understood, due to the lack of historical information.

8. Caveats-social

Biomass is not always a popular solution. Proposals for coordinated energy-forest harvest programs do not enjoy unequivocal public support. Reports that rates of wood harvest were exceeding sustainable yields in many of the world's forested and developing regions and corrective responses such as tree planting, demand reduction programs (de Montalembert and Clement, 1983) reduced emissions from deforestation and forest degradation (REDD in post-2012 climate treaty) have reinforced the association between biomass energy and negative environmental impacts. Fuelwood consumption for energy or heat is often perceived as unsustainable because of its association with deforestation and/or forest degradation, and communicating the use of current logging residues is therefore of paramount importance to gain widespread support for bioenergy programs.

8.1. Caveats-economic

There were several economic assumptions made in this study. There is a substantial transition cost on behalf of households and biomass processing infrastructure associated with the proposed program that could be partly financed by heat cost savings. Even though a sensitivity analysis was conducted that fluctuated fuel prices and efficiency, drastic market volatility was not modeled. The study also assumed that the biomass extraction of material was conservative at 21 to 35 Mg/ha of logging residues. Cost estimates for thinning operations on POW are around 10,900 US$/ha and produce in average 56 Mg/ha in roundwood, offsetting 50% of thinning costs (TNC Alaska, 2013). At a logging residue quantity of 21 Mg/ha and a total requirement of 31,371 Mg/year of biofuel, around 1500 ha/year would need to be thinned to satisfy demand. In the case where the income from the carbon offset market would be diverted to the forest sector instead of the biomass demand sector, this would generate only 46 US$/ha at a price of 5 US$/Mg CO_2e including an overhead of 20%. In this case, the shortfall of 5450 US$/ha in thinning costs would be reduced by less than 1%.

Nevertheless, if thinnings can be financed from other sources than wood products, our results suggest economic gains from a fuel switch. So why does it seem to work so well in this case, where in other parts of the country results are more mixed? In part, because in isolated, geographically challenged small communities, the bar for opportunity cost is quite low because the transport costs of fossil fuels are so high. The size and distribution of the communities are small enough that they do not have access to more traditional cost-efficient systems such as natural gas, and the infrastructural limitation is high. Transportation distance is one of the key variables in determining the viability of a biomass program, and is often the key variable that kills a project. Our study area happens to be in the middle of the biomass supply limiting the issues associated with biomass transportation. A sustainable feed stock supply is also another major limiting factor in making a biomass program viable. Typically the feedstock is planned years in advance from multiple sources including orchard plantations, mill waste, and other alternatives to typical forest streams. This diversity can cause some risk in the supply chain jeopardizing overall performance. From a location perspective, unlike communities located at great distance from the fuel source, the study site communities are located amidst a high volume of reliable feed-stock, so given the scale of the demand relative to supply — the likelihood of reliable supply is higher and much more stable than the typical example.

This approach could yield a natural positive feedback loop depending on how it is scaled. An economy of scale could be created when resources/employment opportunities are close together, using a clustered node system, with a goal of linking back to restoration efforts. There currently is a shifting management regime from clearcutting to a structurally homogenous forest cover/disturbance regime. New restoration efforts have several objectives including opening gaps, creating structural diversity, and preserving wildlife habitat. But these efforts incur major social, ecological and economic costs. Therefore economic costs can be mediated by bundling to environmental and economic costs of fuel on POW. This would create a situation where restoration efforts provide feedstock, and an economically viable alternative that is specifically valuable to that area.

Establishing forest product clusters, and enabling their success can take time, but can be a worthy investment for the POW Island network. The White Mountain Stewardship Project (Apache–Sitgreaves National Park, Arizona), about five years in progress, still receives government support to carry out treatments, and the stewardship projects are only five years in, but managers report progress (Nicholls, personal comm.). It is hoped that within five years, enough wood product firms will be in operation across one or more clusters that treatments will be paid for through energy savings.

Realizing revenues from carbon offsets through the voluntary carbon market might be feasible, though unprecedented as of yet in the US, and could provide limited financial support to support thinning operations on POW while fostering a switch to biomass-based heating applications on POW (Magnani et al., 2007). The nature of such a piloting effort is likely to depend on considerable efforts to protocol eligibility. Residential heating applications are at a considerable disadvantage due to shorter expected project lifetimes and therefore substantially reduced revenues compared to projects providing biomass to commercial-scale combustion facilities.

9. Conclusion

This study quantifies chain of production impacts; from the point of energy extraction and transport (upstream), through consumption and emission accounting (downstream). The model utilized can be adapted for future feasibility analysis as knowledge and data improve. Inputs can be altered based on new parameters, pathways and assumptions. Scenario output can facilitate dialog between land managers, planners, community members and decision-makers. We found that GHG emission savings are substantial and indifferent of biomass sorting lot and transportation pathway. A biomass heating project as described here would be a piloting exercise if endorsed by the emission offset market. Revenues from selling carbon credits can assist in building necessary bioenergy infrastructure but are marginal in terms of the capital required. The conservation of natural capital, typically defined as retention of land cover can be degraded, or restored through management activity. There is evidence that the push for biomass thinning improves natural capital in Southeastern Alaska's forests while also providing benefits for financial capital. However, to overcome logistical limitations, coordination and cooperation must occur at various scales. Future research should focus on forest carbon cycling under thinning regimes and socio-economic variables such as transition costs in the heating systems, assessment of market volatility, and policy incentives, including carbon offset markets, for getting home-owners to shift to wood-based heat.

Acknowledgments

We acknowledge the financial support for this study by The Nature Conservancy Alaska. Maureen Puettmann, Allen Brackley, Dave Nicholls, and Robert Deal as well as two anonymous reviewers provided helpful comments to earlier versions of this manuscript.

Appendix A. Supplementary Data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.ecolecon.2014.08.011.

References

Alaback, P.B., 1982a. Dynamics of understory biomass in Sitka spruce–western hemlock forests of southeast Alaska. Ecology 63, 1932–1948.

Alaback, P.B., 1982b. Forest community structural change during secondary succession in southeast Alaska. In: Means, J.E. (Ed.), Proceedings of the Symposium on Forest Succession and Stand Development Research in the Northwest. Forestry Research Laboratory, Oregon State University, Corvallis, OR, pp. 70–79.

Alaback, P.B., 1984. Plant succession following logging in the Sitka spruce-western hemlock forests of southeast Alaska: implications for management (Gen. Tech. Rep. No. PNW-173). USDA Forest Service, Pac. NW. Forest and Range Exp. Sta, Portland, OR, (26 pp.).

Alaback, P. 2010. An evaluation of canopy gaps in restoring wildlife habitat in second growth forests of Southeastern Alaska. Final Report February 20, 2010 Unpublished Manuscript. The Nature Conservancy-Alaska, Thorne Bay Ranger District and Craig Ranger District, Tongass National Forest, and POWTEC.

Alaska, T.N.C., 2013. KMRD Wildlife Restoration Proposal. Juneau, AK, (6 pp.).

Albert, D.M., Schoen, J.W., 2007. A conservation assessment for the coastal forests and mountains coregion of Southeastern Alaska and the Tongass National Forest. In: Schoen, J.W., Dovichin, E. (Eds.), A conservation assessment and resource synthesis for the coastal forests & mountains ecoregion in Southeastern Alaska and the Tongass National Forest. Audubon Alaska and The Nature Conservancy, Anchorage, AK.

Alexander, S.J., Henderson, E.B., Coleman, R., 2010. Economic analysis of southeast Alaska: envisioning a sustainable economy with thriving communities. Forest Service, Alaska Region Publication R10-MB-725, (Juneau, AK, 93 pp.).

Barbour, R.J., Zaborske, R.R., McClellan, M.H., Christian, L.E., Golnick, D., 2005. Young-stand management options and their implications for wood quality and other values. Land. Urban Plan. 72, 79–94.

Barthelmie, R.J., Morris, S.D., Scheter, P., 2008. Carbon neutral Biggar: calculating the community carbon footprint and renewable energy options for footprint reduction. Sustain. Sci. 3, 267–282.

Baichtal, J.E., Swanston, D.N., 1996. Karst landscapes and associated resources: a resource assessment. Gen. Tech. Rep. PNW-GTR-383. 13 p.

Bastianoni, S., Pulselli, F.M., Tiezzi, E., 2004. The problem of assigning responsibility for greenhouse gas emissions. Ecol. Econ. 49, 253–257.

Beck Group, 2009. Transitioning to young growth: Prince of Wales Island, southeast Alaska. Project Report, Feb. 2009, for The Nature Conservancy. Juneau AK, (58 pp. with appendices).

Beier, C.M., Patterson, T.M., Chapin, F.S., 2008. Ecosystem services and emergent vulnerability in managed ecosystems: a geospatial decision-support tool. Ecosystems 11 (6), 923–938.

Berndes, G., Hoogwijk, M., van den Broek, R., 2003. The contribution of biomass in the future global energy supply: a review of 17 studies. Biomass Bioenergy 25, 1–28.

Beynon, M.J., Munday, M., 2008. Considering the effects of imprecision and uncertainty in ecological footprint estimation: an approach in a fuzzy environment. Ecol. Econ. 373–383 (insert vol).

Buchholz, T., Canham, C., 2011. Forest Biomass and Bioenergy: Opportunities and Constraints in the Northeastern U.S. Cary Institute of Ecosystem Studies, Millbrook, NY, (76 pp.).

Buchholz, T., Da Silva, I., 2010. Potential of distributed wood-based biopower systems serving basic electricity needs in rural Uganda. Energy Sustain. Dev. 14 (1), 56–61.

Caro, D., Bastianoni, S., Borghesi, S., Pulselli, F.M., 2014. On the feasibility of a consumer-based allocation method in national GHG inventories. Ecol. Indic. 36, 640–643.

CCAR (California Climate Action Registry), 2009. California Climate Action Registry General Reporting Protocol, (Version 3.1. Los Angeles CA, USA, 132 pp.).

CDM UNFCCC, 2013a. AMS I.E. Switch from non-renewable biomass for thermal applications by the user. http://cdm.unfccc.int/methodologies/DB/WHTQUFLWCVNB9CIUZC198A712WGQR4 (last accessed December 15, 2013).

CDM UNFCCC, 2013b. Fuel switch from fossil fuels to biomass residues in heat generation equipment AM0036/version 04.0.0. https://cdm.unfccc.int/methodologies/DB/7P3CG1OWTTS3XX0N9XKCENFI050SH6/view.html (last accessed December 15, 2013).

CDM UNFCCC, 2013c. Thermal energy production with or without electricity AMS I.C. Version 19.0 http://cdm.unfccc.int/methodologies/DB/6EL4AG49US2S1DNH55Y4S7GDQFA2JF (last accessed December 15, 2013).

CDM UNFCCC, 2013d. Methodological tool to determine the remaining lifetime of equipment (version 01). http://cdm.unfccc.int/methodologies/PAmethodologies/tools/am-tool-10-v1.pdf (last accessed December 15, 2013).

Costanza, R., 1996. Ecological economics: reintegrating the study of humans and nature. Ecol. Appl. 6, 978–990.

de Montalembert, M.R., Clement, J., 1983. Fuelwood supplies in the developing countries, FAO forestry paper; 42, Rome, 1983. 125 p.

Deal, R.L., 1999. The effects of partial cutting on stand structure and growth, and forest plant communities of western hemlock–Sitka spruce stands in southeast Alaska. (Ph.D. Dissertation) Oregon State University, Corvallis, OR, (191 pp.).

Deal, R.L., 2001. The effects of partial cutting on forest plant communities of western hemlock–Sitka spruce stands in southeast Alaska. Can. J. For. Res. 31, 2067–2079.

Deal, R.L., Tappeiner II, J.C., 2002. The effects of partial cutting on stand structure and growth of western hemlock–Sitka spruce stands in southeast Alaska. For. Ecol. Manage. 159, 173–186.

Deal, R.L., Oliver, D.D., Bormann, B.T., 1991. Reconstruction of mixed hemlock–spruce stands in coastal southeast Alaska. Can. J. For. Res. 21, 643–654.

Deal, R.L., Tappeiner II, J.C., Hennon, P.E., 2002. Developing silvicultural systems based on partial cutting in western hemlock–Sitka spruce stands of southeast Alaska. Forestry 75, 425–431.

Deal, R.L., Barbour, R.J., McClellan, M.H., Parry, D.L., 2003. Development of epicormic sprouts in Sitka spruce following thinning and pruning in southeast Alaska. Forestry 76, 401–412.

Dellasala, D.A., Hager, J.C., Engel, K.A., McComb, W.C., Fairbanks, R.L., Campbell, E.G., 1996. Effects of silvicultural modifications of temperate rainforest on breeding and wintering bird communities, Prince of Wales Island, southeast Alaska. Condor 98, 706–721.

Giarola, S., Shah, N., Bezzo, F., 2012. A comprehensive approach to the design of ethanol supply chains including carbon trading effects. Energy Policy 107, 175–185.

Hanley, T.A., 1993. Balancing economic development, biological conservation, and human culture: the Sitka black-tailed deer (*Odocoileus hemionus sitkensis*) as an ecological indicator. Biol. Conserv. 66, 61–67.

Hanley, T.A., 1996. Small mammals of even-aged, red alder-conifer forests in southeastern Alaska. Can. Field Nat. 112, 647–652.

Hanley, T.A., 2005. Potential management of young-growth stands for understory vegetation and wildlife habitat in southeastern Alaska. Landsc. Urban Plan. 72, 95–112.

Hanley, Thomas A., McClellan, Michael H., Barnard, Jeffrey C., Friberg, Mary A., 2013. Precommercial Thinning: Implications of Early Results from the Tongass-Wide Young-Growth Studies Experiments for Deer Habitat in Southeast Alaska. Res. Pap. PNW-RP-593. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, (64 pp.).

Helms, J.A. (Ed.), 1998. The Dictionary of Forestry. Society of American Foresters, Bethesda, MD. National Research Council, 2000. Environmentall issues in Pacific Northwest Forest Management. National Academy Press, Washington, DC.

Hennon, P.E., McClellan, M.H., 2003. Tree mortality and forest structure in temperate rain forests of southeast Alaska. Can. J. Forest Res. 33, 1621–1634.

Hertwich, E.G., Peters, G.P., 2009. Carbon footprint of nations: a global, trade linked analysis. Environ. Sci. Technol. 43 (16), 6414–6420.

Horne, R.E., Bates, M., Fien, J., Kellett, J., Hamnett, S., 2007. Carbon neutral communities: definitions and prospects. CNC Working Paper No. 1 (draft).

Hurteau, M.D., North, M., 2010. Carbon recovery rates following different wildfire risk mitigation treatments. For. Ecol. Manage. 260, 930–937.

ISO (International Organization for Standardization), 2006. Standards catalogue ISO/TC 207/SC 5 — life cycle assessment. http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_tc_browse.htm?commid=54854 (last accessed December 15, 2013).

Kim, B., Neff, R., 2009. Measurement and communication of greenhouse gas emissions from U.S. food consumption via carbon calculators. Ecol. Econ. 69, 186–196.

Korobeinikov, A., Read, P., Parshotam, A., Lermit, J., 2010. Modelling regional markets for co-produced timber and biofuel. Ecol. Econ. 69 (3), 553–561.

Leighty, W.W., Hamburg, S.P., Caouette, J., 2006a. Effects of management on carbon sequestration in forest biomass in southeast Alaska. Ecosystems 9, 1051–1065.

Leighty, W., Holloway, J., Merer, R., Somerday, B., San Marchi, C., Keith, G., et al., 2006b. Compressorless hydrogen transmission pipelines deliver large-scale stranded renewable energy at competitive cost. Proceedings of the 16th World Hydrogen Energy Conference, Lyon, FR. vol. 6 (June).

Lowell, E.C., Monserud, R.A., Clark, A.I.I.I., 2008. Pre-commercial thinning in southeast Alaska and its impact on wood quality. In: Deal, R.L. (Ed.), Integrated Restoration of Forested Ecosystems to Achieve Multiresource Benefits: Proceedings of the 2007 National Silviculture Workshop. Gen. Tech. Rep. PNW-GTR-733. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, pp. 295–296 (306 pp.).

Magnani, F., Mencuccini, M., Borghetti, M., Berbigier, P., Berninger, F., Delzon, S., et al., 2007. The human footprint in the carbon cycle of temperate and boreal forests. Nature 447, 849–851.

Mann, M., Spath, P.L., 2001. A life cycle assessment of biomass cofiring in a coal-fired power plant. Clean Prod. Process. 3, 81–91.

Matthews, S., Hendrickson, C.T., Weber, C.L., 2008. The importance of carbon footprint estimation boundaries. Env. Sci. Technol. 42 (16), 5839–5842.

McClellan, M.H., 2008. Adaptive management of young stands on the Tongass National Forest. In: Deal, R.L. (Ed.), Integrated Restoration of Forested Ecosystems to Achieve Multiresource Benefits: Proceedings of the 2007 National Silviculture Workshop. Gen. Tech. Rep. PNW-GTR-733. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, pp. 225–232 (306 pp.).

McClellan, M.H., Swanston, D.N., Hennon, P.E., Deal, R.L., De Santo, T.L., Wipfli, M.S., 2000. Alternatives to Clearcutting in the Old-growth Forests of Southeast Alaska: Study Plan and Establishment Report. Gen. Tech. Rep. PNW-GTR-494. USDA Forest Service, Pacific Northwest Research Station, Portland, OR, (40 pp.).

Mitchell Group, Inc., 2003. Promoting Competitiveness in Practice: An Assessment of Cluster-based Approaches. The Mitchell Group, Washington, DC, (112 pp. http://www.bdsknowledge.org/dyn/bds/docs/254/USAID-Mitchell-Clusters.pdf (last accessed December 15, 2013)).

Munnich, L.W., Schuh, G., Lenhoff, J., Murray-Close, M., Bates, T., Pesch, R., Wachira, W., 2003. Rural knowledge clusters: innovation and vitality in America's rural communities. U.S. Department of Agriculture, Cooperative State Research, Education, and Extension Service (CSREES) Fund for Rural America September 2003, (62 pp. http://www.hhh.umn.edu/centers/slp/economic_development/documents/rkc_year2report.pdf (last accessed December 15, 2013)).

Oliver, C.D., 1981. Forest development in North America following major disturbances. For. Ecol. Mgmt. 3, 153–168.

Oliver, C.D., Larson, B.C., 1996. Forest Stand Dynamics. John Wiley and Sons, New York, 544 pp.

Patrizi, N., Caro, D., Pulselli, F.M., Bjerre, A.B., Bastianoni, S., 2013. Feasibility of partial substitution of gasoline with ethanol in Siena Province (Italy): an LCA approach. J. Clean. Prod. 47, 388–395.

Pearce, D.W., Atkinson, G.D., 1993. Capital theory and the measurement of sustainable development: an indicator of weak sustainability. Ecol. Econ. 8, 103–108.

Perlack, R.D., Wright, L.L., Turnhollow, A.F., Graham, R.L., Stokes, B.J., Erbach, D.C., 2005. Biomass as feedstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual supply. Oak Ridge National Laboratory, Oak Ridge, TN, 59 p.

Peterson, C.E., Monserud, R.A., 2002. Compatibility Between Wood Production and Other Values and Uses on Forested Lands: A Problem Analysis. Gen. Tech. Rep. PNW-GTR-564. USDA Forest Service, Pacific Northwest Research Station, Portland, OR, (51 pp.).

Pierce, J.T., 1996. The conservation challenge in sustaining rural environments. J. Rural. Stud. 12 (3), 215–229.

Porter, M.E., 1990. The Competitive Advantage of Nations. The Free Press, New York, (857 pp.).

Ridolfi, R., Kneller, M., Donati, A., Puslelli, R., 2008. The greenhouse gas balance of the province of Siena. J. Environ. Manag. 86, 365–371.

Rogers, M., Ryan, R., 2001. The triple bottom line for sustainable community development. Local Environ. Int. J. Justice Sustain. 6 (3), 279–289 (1469-6711).

Rojas, T.D., 2007. National forest economic clusters: a new model for assessing national-forest-based natural resources products and services. United States Department of Agriculture Forest Service Pacific Northwest Research Station General Technical Report PNW-GTR-703, (40 pp.).

Schoen, J.W., Wallmo, O.C., Kirchhoff, M.D., 1981. Wildlife–forest relationships: is a reevaluation necessary? Trans. N. Am. Wildl. Nat. Resour. Conf. 46, 531–544.

Schoen, J.W., Kirchhoff, M.D., Hughes, J.H., 1988. Wildlife and old-growth forests in southeastern Alaska. Nat. Areas J. 8, 138–145.

Smith, G.R., 1998. Are we leaving the community out of rural community sustainability? Int. J. Dev. World Ecol. 5 (2), 82–98.

Tappeiner, J.C., Alaback, P.B., 1989. Early establishment and vegetative growth of understory species in the western hemlock–Sitka spruce forests in southeast Alaska. Can. J. Bot. 67, 318–326.

U.S. Department of Energy, 2011. U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry. R.D. Perlack and B.J. Stokes (Leads), ORNL/TM-2011/224. Oak Ridge National Laboratory, Oak Ridge, TN, (227 pp.).

U.S. Environmental Protection Agency, 2008. Direct Emissions from Stationary Combustion Sources. Washington DC, USA. , (36 pp. http://www.epa.gov/climateleadership/documents/resources/stationarycombustionguidance.pdf (last accessed December 15, 2013)).

Wallmo, O.C., Schoen, J.W., 1980. Response of deer to secondary forest succession in southeast Alaska. For. Sci. 26, 448–462.

Wei, T., Dong, W., Yuan, W., Yan, X., Guo, Y., 2014. Influence of the carbon cycle on the attribution of responsibility for climate change. Chin. Sci. Bull. 59 (19), 2356–2362.

Wennberg, K., Lindqvist, G., 2010. The effect of clusters on the survival and performance of new firms. Small Bus. Econ. 34 (3), 221–241.

Zaborske, R.R., Hauver, R.N., McClellan, M.H., Hanley, T.A., 2002. Understory vegetation development following commercial thinning in southeast Alaska: preliminary results from the Second-growth Management Area Demonstration Project. Beyond 2001: a silvicultural odyssey to sustaining terrestrial and aquatic ecosystems. In: Parker, S., Hummel, S. (Eds.), Proceedings of the National Silviculture Workshop. Gen. Tech. Rep. PNW-GTR-546. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, pp. 74–82.

Zanchi, G., Frieden, D., Pucker, J., Bird, N., Buchholz, T., Windhorst, K., 2013. Climate benefits from alternative energy uses of biomass plantations in Uganda. Biomass Bioenergy 59, 128–136.