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A carbon balance assessment for containerized *Larix gmelinii* seedlings in the Russian Far East

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Abstract

A carbon balance assessment for containerized *Larix gmelinii* seedlings in the Russian Far East determined that the level of carbon emitted to the atmosphere as a result of inputs used in the seedling growing process exceeded the volume of carbon sequestered by the seedlings at a ratio of approximately 1:40 (one part sequestered carbon to 40 parts carbon emissions). Seedlings were raised at the Nekrasovka Greenhouse Complex, Khabarovskii krai, Russian Federation, during 1998–2000. The amount of carbon sequestered by the seedling growth prior to out-planting was determined by mass spectrometry. Seedling production resulted in an initial carbon deficit, defined as the net carbon released to the atmosphere in the form of carbon dioxide (CO_2). On average, each seedling raised at the greenhouse complex brought about the emission of 76.4 g of carbon dioxide from production inputs, the equivalent of 20.8 g of carbon per seedling. Averaged over three, 1 year production cycles, the carbon content of the seedlings was approximately 0.516 ± 0.078 g per seedling, resulting in a 20.28 g carbon deficit per seedling (equivalent to a 74.36 g atmospheric carbon dioxide deficit). To offset this initial deficit, seedlings would need to grow to an estimated 74.68 cm in total tree height after out-planting. In boreal forests of the Russian Far East, this would require approximately 3–10 years with time varying depending on specific site conditions.

Keywords: Carbon sequestration; Carbon balance; Russia; Boreal forests; *Larix gmelinii*; Gmelina larch; Reforestation

1. Introduction

Anthropogenic emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) have increased from the mid-19th century to the beginning of the 21st century by approximately 30, 145 and 15%, respectively (IPCC, 1995). Atmospheric levels of carbon dioxide have increased over the same period from an estimated 280 parts per million by volume (ppmv) (Bolin et al., 1977) to present day levels of approximately 360 ppmv (IPCC, 1995; Nilsson et al., 2000). Higher concentrations of greenhouse gasses reduce the ability of the Earth to radiate planetary heat through the atmosphere. Most scientists agree that the increases in greenhouse gases are a major cause in the observed trend of global climate warming (IPCC, 1995).

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Plants in both terrestrial and aquatic ecosystems withdraw carbon dioxide from the atmosphere in the process of photosynthesis. Carbon sequestered from the atmosphere is stored in plant fiber (above and below ground) for extended periods of time, especially in perennial plants such as trees (see Bolin et al., 1977; IPCC, 1995, for discussions). Higher atmospheric carbon dioxide levels, combined with increased atmospheric nitrous oxide, contribute to enhanced plant productivity generally and, consequently, the rate at which carbon dioxide is removed from the atmosphere (Hollinger et al., 1995; Schulze et al., 1995; Burton, 1997). Therefore, there is some possible homeostatic feedback effect wherein more emissions induce a greater uptake of carbon. On the other hand, increased warming enhances decomposition of detritus on and in soils. The magnitude of these combined biological processes, as well as many other sources of carbon emissions and assimilation, remains largely undetermined. However, it is clear that terrestrial and aquatic ecosystems have been unable to offset increased emissions of carbon dioxide from the burning of fossil fuels, forest fires, and other sources as evidenced by rising atmospheric carbon dioxide levels.

Boreal forests are the most widespread vegetation type in the northern hemisphere (Schulze et al., 1999). The world's boreal forests are considered an important sink for atmospheric carbon; both above- and belowground. The Russian taiga (boreal forest) encompasses some 1709.4 million ha (4223.9 million acres) (Nilsson et al., 2000) with 884 million ha (2184 million acres) in the boreal forest zone—nearly half of the world's boreal forest reserve (Krankina et al., 1997). Species of *Larix* are an important component of the Russian boreal forest zone, occupying vast areas across its range (Kuvaev and Stetsura, 1985; Abaimov et al., 1997; Kajimoto et al., 1999). The role of *Larix* species in the boreal forest ecosystem is noteworthy because of its ability to establish and grow on poor soils and on steep slopes prone to erosion and mass wasting, and its ability to withstand extremely cold winter-time temperatures while tolerating periodic summer-time forest fires common to the region (Kuvaev and Stetsura, 1985).

Global warming is expected to reduce net carbon sequestration abilities of such forests by up to 50% due primarily to enhanced rates of soil and detritus decomposition (Manabe and Wetherald, 1987). Nilsson et al. (2000) have estimated that from the period 1961–1983 Russia experienced a net sequestration of 10.1 $\mathrm{g\,C\,m^{-2}}$ per year (0.2979 $\mathrm{oz\,C\,yd^{-2}}$ per year) into the soil. This trend reversed between 1984 and 1994 and these forests became a net source of carbon emissions into the atmosphere at the rate of 7.1 $\mathrm{g\,C\,m^{-2}}$ per year (0.2094 $\mathrm{oz\,C\,yd^{-2}}$ per year) due to anthropogenic and natural disturbances.

Forest preservation, large-scale reforestation, and aforestation efforts have been proposed as actions that will help mitigate global climate change by increasing long-term carbon sequestration capacity. The American Forestry Association (2000) Internet web site even offers an interactive page for calculating how many trees a year a household must plant to offset their greenhouse gas contributions to global warming (increased tree planting would also offer additional ecological and economic benefits).

The net amount of carbon sequestered as a result of reforestation or aforestation efforts must consider carbon costs (from carbon dioxide emissions) of seedling husbandry, planting, and managing the forests, as well as the changes caused to carbon pools as a result of the activity. Fig. 1 presents a rough schematic of the carbon pools (sinks and sources) influenced by tree planting and forest management. Our study addresses only one aspect of this large and complex issue. Specifically, we focus on the 'carbon cost' of raising containerized seedlings at a greenhouse facility, destined for forestry out-planting in the Russian boreal forest. We estimate a net carbon cost at the point of out-planting by also calculating the amount of carbon sequestered in the seedling.

We use a carbon balance approach related to the life cycle assessment (LCA) method. Variations of the LCA approach have been used on many projects globally (see, e.g., Aycaguer et al., 2001; Vehar, 2001; Börjesson and Gustavsson, 2000; McCann and Magee, 1999; AFPA, 1996; Atkinson et al., 1996; Komiyama et al., 1996; Nieuwlaar et al., 1996) to determine the environmental burden for a process or service during the life of a project, or a specific phase of an undertaking (Ayres, 1995; Heijungs and Guinée, 1992). In our study, we evaluate only carbon dioxide emissions to the environment caused by raising containerized conifer seedlings—beginning with the processing of collected cones and ending with the preparation of shipping the seedlings to forestry units in the region. We focus on a

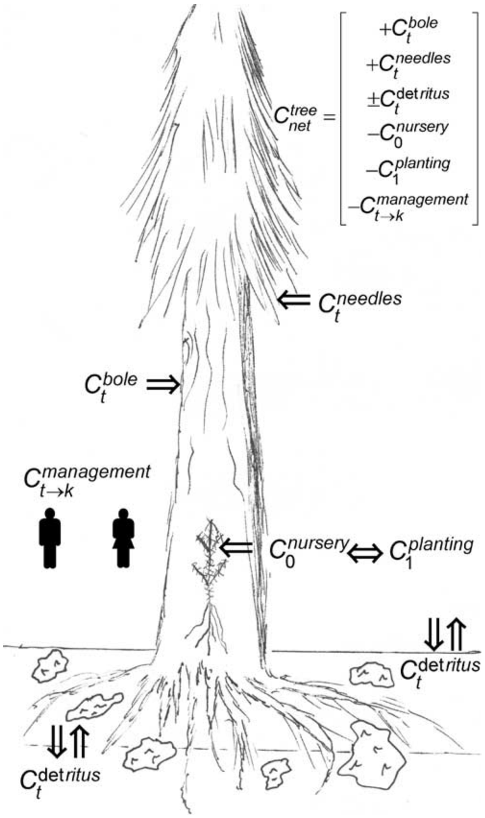

Fig. 1. Potential carbon sinks and sources involved with raising a containerized seedling to a mature tree. C represents carbon, the subscripts denote a time index beginning at year zero (0) in the greenhouse and going to year '*k*', which is any year being considered in the net sequestration determination. Superscripts indicate sources of carbon emissions when coupled with a '−' and sinks of carbon when coupled with a '+'.

Table 1
Inputs to raising containerized tree seedlings that are also potential sources of carbon emissions to the atmosphere

Component	Magnitude of C emissions	Inclusion in this research
Electricity		
Used at greenhouse complexes	Major	Yes
Used at seed storage freezers	Major	Yes
Used at seedling storage coolers	Major	Yes
Petroleum products		
Vehicles	Potentially major	Yes
Generators and other motors	Potentially major	Yes
Growth stimulants and media		
Fertilizers	Major	Yes
Perlite	Insignificant	Yes
Peat moss	Insignificant	No
Building supplies and infrastructure		
Cement	Major	Yes
Metals (especially steel)	Major	Yes
Polyethelene resin plastics	Carbon sink	Yes
Lumber (from manufacturing process)	Carbon sink	No
Tree planting activities		
Forest site preparation	Potentially major	No
Vehicle fuel for transporting people and seedlings to the forest site	Minor	No
Forest management activities	Minor	No

specific greenhouse complex in the Russian Far East. This 'cone-to-seedling' (*to the farm gate*) approach allows the forest manager to receive seedlings with a 'carbon cost' prior to planting in various forest conditions. The carbon dioxide cost of seedling transportation and planting in the boreal forest is highly variable and must be assigned by the forest manager where the seedlings will be raised; these post greenhouse activities were not considered in this research.

Many activities involved in growing containerized seedlings in greenhouses create a net release of carbon dioxide to the atmosphere that is not immediately sequestered by the seedlings the practice produces (Table 1). These carbon dioxide emissions must be offset against the sequestration of the tree seedlings in determining the net carbon balance. To date, there have been no comprehensive studies employing the LCA approach to determine the net carbon dioxide emissions cost of raising containerized seedlings in a commercial greenhouse setting.

This carbon balance assessment focuses on the activity of raising containerized seedlings at the Sosnovka Seed Breeding Center (48.43°N, 135.13°E) in the Russian Far East region of Khabarovskii krai (krai, republic, oblast, autonomous bodies, and okrugs are administratively similar to 'states' in the USA) (Fig. 2). The seedlings referenced in this study were raised at the Center's Nekrasovka Greenhouse Complex and were used to repopulate boreal forests in the Russian Far East that were harvested or burnt by forest fires. Gmelina larch (*Larix gmelinii* (Rupr.) Kuzeneva), Korean pine (*Pinus koraiensis* Siebold

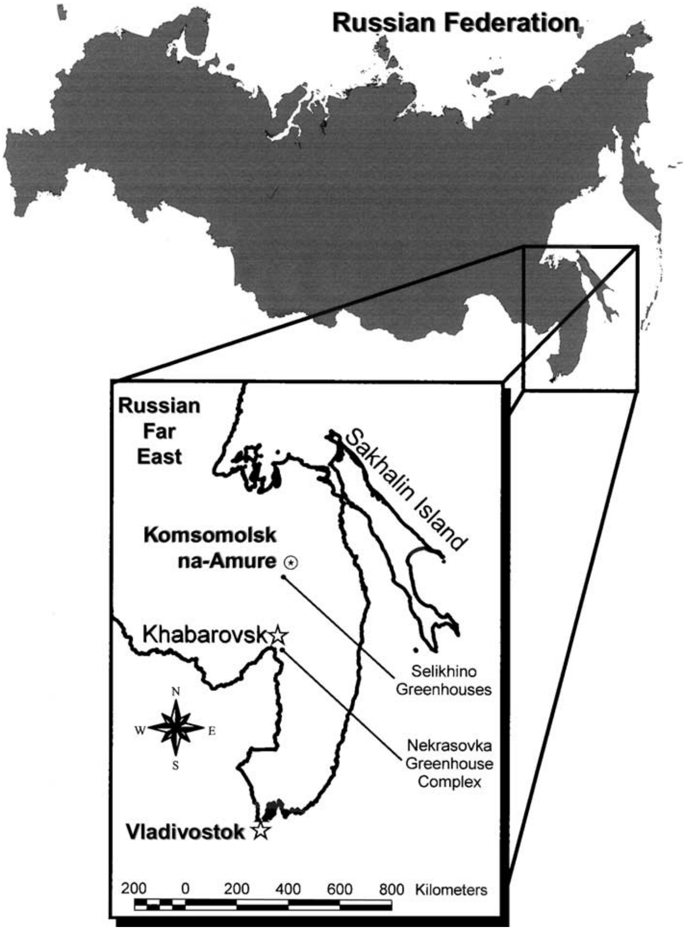

Fig. 2. Russian Far East greenhouse locations of the Sosnovka Seed Breeding Center in the Russian Far East.

and Zucc.), and spruce (*Picea ajanensis* (Lindl. et Gord.) Fisch. ex Carr.) are all produced at this facility. Two greenhouses were operational in 1998 (500,000 seedlings) and a third greenhouse was added in 1999. The annual total number of seedlings in 1999 and 2000 raised in the three-greenhouse complex was 700,000 and 755,700, respectively (Table 2). The primary species raised at this facility is Gmelina larch.

Seed is extracted from cones, then cleaned and stored in a dedicated freezer facility. Each spring seedlings are sown into containers, raised for one season (April–October) in a greenhouse, and then

Table 2
Containerized seedling production at the Nekrasovka Greenhouse Facility in Khabarovskii krai, Russian Federation

Year	Tree species				
	L. gmelinii	*P. ajanensis*	*P. koraiensis*	Other	Total
1998	500,000	0	0	0	500,000
1999	700,000	0	0	0	700,000
2000	700,000	3900	22,100	29,700	755,700

placed in a dedicated winter storage cooler prior to outplanting in the forest the following spring; each seedling spends only one growing season at the greenhouse facility. Our study was based on three growing seasons from 1998 to 2000; data represented for each year represent a new and unique batch of seedlings.

Only carbon dioxide emissions were evaluated. Other greenhouse gases were not assessed. Some of the seedling production activities caused carbon dioxide to be released into the atmosphere directly in the production of seedlings (e.g., petroleum combustion). In other cases, carbon dioxide is released into the atmosphere in the production of inputs used in seedling production (e.g., cement and fertilizer production). Although there are additional activities that cause carbon dioxide to be released to the atmosphere during nursery production (Table 1), generally these other sources are minor relative to those evaluated—some are discussed briefly in this manuscript. While not the focus of the paper, some other greenhouse gasses are mentioned in relation to their interaction with carbon dioxide.

The objectives of the study were to: (1) evaluate the amount of carbon released to the atmosphere as a direct result of raising containerized conifer seedlings in the Russian Far East; (2) calculate a seedling carbon ‘initial deficit’; and (3) provide tools for estimating the time required for seedlings to ‘pay back’ their carbon deficit and represent a net carbon sequestration gain to the environment. These findings should prove useful in assessing the overall lifecycle carbon sequestration of Russian boreal forests. The methods developed here may also provide a useful framework for additional studies in other forest systems.

2. Methods and data

2.1. Carbon dioxide emissions from production

Table 1 lists the main carbon emitting activities at the seed breeding center which used electricity produced by regional coal burning facilities. Grass-peatmoss was the main potting media. Perlite was used as a seed covering at the time of seed sowing. Liquid fertilizers were applied to the seedlings recurrently during the growing season. Fuel-powered trucks, tractors, and automobiles were used in the management and operation of the seed breeding center. An electric water pump (with a gas-powered back-up) pulled water from a well and then pressurized water lines supplying an electric powered irrigation unit. Two gasoline powered electric generators provided back-up power supply for the greenhouse facility while one diesel-powered generator provided back-up electrical support at the freezer-and-cooler complex, when the regional power supply was off-line.

Carbon dioxide discharge from the listed activities was determined using results from a variety of studies conducted by the US Environmental Protection Agency (EPA), production information (inputs and outputs) included in the US Census of Manufacturers, independent research studies, and emission statistics published for various energy sectors in Russia. The Sosnovka Seed Breeding Center reported actual seedling production (Table 2) and the corresponding annual usage of listed inputs such as fuel, electricity, fertilizer, and perlite (Table 3). The volume of cement and the weight of steel used in construction were recorded directly from construction records.

2.2. Carbon sequestration by seedlings

Seedlings raised at the Sosnovka Seed Breeding Center’s Nekrasovka Greenhouse Complex during the year 2000 were sampled to determine their oven-dry weight (ODW) and carbon content. We estimated that the *L. gmelinii* seedlings from the year 2000 were representative of 1998 and 1999 production in terms of culture and management regime of that particular species, and therefore we estimated that their average weight and carbon content would be representative of the previous years.

Three seedling container sizes (distributed by Stuewe and Sons, Corvallis, OR, USA: Rigi-Pots 45–70, 45–95 and 45–110) were used at the greenhouse complex during the three years evaluated in this study: 70 ml (80 mm deep), 95 ml (100 mm deep), and 110 ml (120 mm deep). The latter two were primarily used in the culture of larch species, while the 70 ml container was used primarily for raising Korean pine seedlings, with a small number used to raise larch seedlings.

During the winter of 2000–2001, 20 larch seedlings from each of the three container sizes were selected at random (60 total) from the seedling winter storage

Table 3
Various input levels to raising containerized seedlings at the Sosnovka Seed Breeding Facility

Year	Component (average CO_2 emissions, expressed as a percentage of total over 3-year period)	Component usage	Annual CO_2 cost (kg)
1998	Electricity at greenhouses (28.5%)	17,000 kW h	140,12.1
1999		17,500 kW h	144,24.3
2000		17,100 kW h	140,94.6
1998	Electricity at freezer-and-cooler facility (16.9%)	10,200 kW h	8407.3
1999		10,200 kW h	8407.3
2000		10,200 kW h	8407.3
1998	Petroleum used at all locations (5.4%)	4000 l	2532.4
1999		4500 l	2848.9
2000		4300 l	2722.3
1998	Fertilizer manufacture (from burning natural gas) (24.0%)	1225 kg	9162.6
1999		1715 kg	128,27.6
2000		1850 kg	138,37.4
1998	Perlite manufacture (0.1%)	45 kg	19.6
1999		68 kg	29.6
2000		68 kg	29.6
1998	Cement usage (11.9%)	Averaged over 20-year life	5797.0
1999			6002.7
2000			6002.7
1998	Steel usage (13.3%)	Averaged over 20-year life	6624.0
1999			6624.0
2000			6624.0
1998	Total of listed sources		465,55.0
1999			511,64.4
2000			517,17.9

cooler, and ODW of each seedling was determined. Since the seedlings were larch, needles were not present. Each seedling was cleaned of substrate matter (peat moss and perlite), numbered, and then placed in an oven at 70 °C (158 °F) and dried to constant mass.

A separate sample of 12 seedlings raised in greenhouses utilizing polyethelene covering on the frame of the greenhouse, and another sample of 10 seedlings from a greenhouse covered with non-polyethelene resin plastic were taken. Both were random samples from the 95 and 110 ml containers. These seedlings were oven-dried, ground, placed in containers, and labeled. The percent composition of carbon was determined for each of the 22 seedling samples at the Idaho Stable Isotopes Laboratory, University of Idaho. Carbon composition was determined using a continuous-flow elemental analyzer coupled with an isotope ratio mass spectrometer (the elemental analyzer used was a CE Instrument's model NC2500 of Milan, Italy; the isotope ratio mass spectrometer used was a Finnigan MAT delta-plus manufactured in Bremen, Germany). The isotope ratio mass spectrometer was used as the detector to determine the precise isotope ratio compositions. Stable isotope composition was recorded per mil as $\delta^{13}C$. Information on the 1998–2000 growing seasons were utilized to link seedling carbon sequestration with seedling production related carbon dioxide emissions.

3. Results

3.1. Electricity production and consumption

Electricity production in the Russian Far East and Siberia derives from coal (75%), hydroelectric (24%), and nuclear (<1%) sources. Energy production in Khabarovskii krai and neighboring Primorskii krai, Sakhalinskaya oblast, and Kamchatskaya oblast is exclusively from power plants burning primarily bituminous coal (Kalashnikov, 1997). This variety of coal supplies 20–29 megajoules (MJ) of energy per kilogram (8616–11,202 BTU lb^{-1}) of coal burned and has a high sulfur content (up to 35%) (McConnell, 1999). The Khabarovsk Economic Research Institute (Kalashnikov, 1997) estimates that the average energy efficiency of these facilities for electricity production is only 31–34%.

One short ton of bituminous coal produces approximately 27,431 MJ (26×10^6 BTU) of energy (Grillot, 2000) and one kilowatt hour (kW h) of electricity requires 3.6 MJ (3412.1412 BTU) (McConnell, 1999). From 1998 to 2000, the Sosnovka Seed Breeding Center's seed freezer and seedling cooler facility used 10,200 kW h of electricity per year (Table 3), consuming 4.1188 short tons of coal as calculated using Eq. (1):

$$\left(\frac{10{,}200\,\mathrm{kW\,h}}{\mathrm{year}\ 2000}\right)\left(\frac{3412.1412\,\mathrm{BTU}}{1\,\mathrm{kW\,h}}\right)\left(\frac{1\ \text{short ton coal}}{26\times10^{6}\,\mathrm{BTU}}\right) \times\left(\frac{1}{0.325}\right) = 4.1188\ \text{short tons coal} \tag{1}$$

where 0.325 = average electrical energy conversion efficiency.

Burning of typical bituminous coal with an energy content of 20–29 MJ kg^{-1} (average 24 MJ) will release 94 g $\mathrm{CO_2\,MJ^{-1}}$ (3.5×10^{-3} oz $\mathrm{CO_2\,BTU^{-1}}$), or 2.25 kg $\mathrm{CO_2\,kg^{-1}}$ of burned coal (Statoil, 2000). Therefore, the electricity produced in support of the freezer-and-cooler complex released 8407.3 kg CO_2 (18,534.6 lb CO_2) into the atmosphere during each year of production (Eq. (2))

$$\left(\frac{4.1188\ \text{short tons coal}}{\text{each year}}\right)\left(\frac{907.2\,\text{kg coal}}{1\ \text{short ton coal}}\right) \times\left(\frac{2.25\,\mathrm{kg\,CO_2}}{1\,\text{kg coal}}\right) = 8407.3\,\mathrm{kg\,CO_2} \tag{2}$$

Results of the calculations for each of the three years evaluated are presented in Table 3 for the freezer-and-cooler complex as well as the greenhouse facilities.

3.2. Petroleum consumption

Gasoline and diesel fuel-powered generators, tractors, and automobiles (cars, trucks, and a bus) are used at the seed-breeding facility. Between 4000 and 4500 l of gasoline and diesel fuel (between 1057 and 1189 gal (US)) were consumed each year from 1998 to 2000 (Table 3).

Carbon dioxide emissions to the atmosphere resulting from the operation of fuel-powered vehicles and equipment were calculated using a 99% conversion factor of carbon in fuel to carbon dioxide and the relationship that diesel fuel is approximately 87% by weight composed of carbon, while gasoline is 86% by weight composed of carbon (EPA, 2000). Considering the year 2000 fuel data, 4300 l (1136 gal (US)) of fuel were consumed (gasoline and diesel combined). The approximate weight of petroleum (at 15 °C) is 0.7393 kg l^{-1} (6.1568 lb gal^{-1} at 59 °F), and the average gasoline and diesel carbon content by weight is 86.5%. The conversion of fuel-bound carbon to atmospheric carbon dioxide from combustion in the year 2000 is 2722.3 kg CO_2 (Eq. (3)) (5989.1 lb CO_2):

$$\left(\frac{4300\,\mathrm{l\ fuel}}{\mathrm{year}\ 2000}\right)\left(\frac{0.7393\,\mathrm{kg\ fuel}}{1\,\mathrm{l\ fuel}}\right)\left(\frac{99\,\mathrm{kg\ carbon}}{100\,\mathrm{kg\ fuel}}\right) \times\left(\frac{86.5\,\mathrm{kg\,CO_2}}{100\,\mathrm{kg\ carbon}}\right) = 2722.3\,\mathrm{kg\,CO_2} \tag{3}$$

Estimates of the carbon dioxide contribution to the atmosphere from fuel combustion at this facility are presented for each of the 3 years in Table 3.

3.3. Growth stimulant usage

The seed breeding center uses a variety of fertilizers and supplements to satisfy the nutrient needs of its seedlings. Included are a pre-emergent fertilizer (9–45–15 at ≈0.24 g per tree per year), a growth fertilizer (20–10–20 at ≈1.70 g per tree per year), a hardening off fertilizer (5–11–26 at ≈0.48 g per tree per year), and an iron supplement (Sprint 330 at ≈0.02 g per tree per year). The facility used 1225 kg (2700 lb) of fertilizers (all combined) in 1998, 1715 kg (3780 lb) in 1999, and 1850 kg (4078 lb) in 2000. All of the fertilizers were mixed on site and applied in liquid form through a fertilizer injector (Dosmatic Plus DP305, Model A30-2.5) into a hanging irrigation system (McConkey, ITS Basic Grower).

Both particulate matter and gaseous air emissions are generated from the application of nutrients as fertilizers. Researchers have observed only nitrogen-based molecule emissions as a result of applying fertilizers (EPA, 2000; Johansson, 1984). There is no evidence to conclude that carbon dioxide is emitted to the atmosphere as a result of fertilizer application per se although small quantities of nitrogen emissions may occur. Therefore, in this study, zero emissions were assumed to occur at the time of fertilizer application.

On the other hand, the fertilizer manufacturing process does release greenhouse gases into the atmosphere. The production of nitrogen fertilizers, including urea, produces small amounts of nitrogen oxides but no reported carbon dioxide is released (EPA, 1993). Production of phosphate fertilizers does not directly contribute additional greenhouse gasses to the atmosphere (Pacific Environmental Services Inc., 1996). However, the burning of natural gas during the manufacturing of fertilizers emits carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x), methane (CH_4), nitrous oxide (N_2O), volatile organic compounds, trace amounts of sulfur dioxide (SO_2), and particulate matter (EPA, 1995).

The exact quantities of greenhouse gasses emitted from the manufacture of fertilizers are still being determined (EPA, 2000). Current available estimates on natural gas emissions were used to estimate carbon dioxide released into the atmosphere (Census, 1999; EPA, 2000). Specifically, the nitrogenous fertilizer manufacturing industry was used as a proxy for the entire fertilizer industry in estimating carbon dioxide release in this study.

The nitrogenous fertilizer manufacturing industry burned 11.13 billion m^3 (393.2 billion standard cubic feet) of natural gas in 1997 in the production of approximately 2.86×10^9 kg (6.3 billion lb) of fertilizer (Census, 1999). Roughly 1.926 kg CO_2 is released into the atmosphere for every cubic meter (0.11998 lb CO_2 ft^{-3}) of natural gas burned (EPA, 2000). The Sosnovka Seed Breeding Center applied 1850 kg (4079 lb) of fertilizers in 2000. Using industry production rates and published carbon dioxide emission rates, the emissions caused by the use of fertilizers at this greenhouse facility are estimated for the year 2000 to be 13,837.4 kg (30,505.7 lb) CO_2 (Eq. (4))

$$\left(\frac{11.13 \times 10^9\,\text{m}^3\ \text{natural gas}}{2.86 \times 10^9\,\text{kg fertilizer}}\right)\left(\frac{1.922\,\text{kg CO}_2}{1\,\text{m}^3\ \text{natural gas}}\right) \times \left(\frac{1850\,\text{kg fertilizer}}{\text{year 2000}}\right) = 13,837.4\,\text{kg CO}_2 \qquad (4)$$

Results for calculations for the other 2 years are shown in Table 3. It is important to note that these are rough estimates using indirect evidence of the emissions of carbon dioxide caused by fertilizer manufacture.

3.4. Perlite consumption

Perlite is a pearl-colored product manufactured from glassy volcanic rock. It is used in the greenhouse industry as a covering over seedling containers immediately after substrate and seeds are placed in the seedling containers. It provides protection for seeds from direct sunlight, water splashing during irrigation, and alleviates the effects of extreme temperature variations during germination. The components of perlite include silicon dioxide (71–75%), alumina (12.5–18%), potassium oxide (4–5%), calcium oxides (1–4%), and trace amounts of metal oxides (EPA, 1995).

The manufacturing process of perlite involves mining, crushing, drying in a rotary dryer, grinding, screening, and shipping to expansion plants where furnaces are operated at temperatures as high as 980 °C (1800 °F). Production rates are normally less than 1800 kg h^{-1} (3960 lb h^{-1}) (EPA, 1995).

Particulate matter is the primary pollutant generated from the manufacture process of perlite. Nitrogen oxides created during perlite expansion are generally negligible (EPA, 1995). Sulfur dioxide (SO_2) emissions may result when sulfur-containing fuels are used in the manufacture process through the mixing of particulate matter (from processing) and exhaust gasses (from machinery). Of most relevance to our analysis of carbon is the fact that the primary fuel source used in the industry is natural gas. Fuel consumption ranges from 2800 to 8960 kilojoules (kJ) per kilogram (2.4×10^6–7.7×10^6 Btu ton^{-1}) of finished product (EPA, 1995).

Operation of expansion furnaces during perlite manufacture releases 420 kg CO_2 Mg per perlite (840 lb CO_2 ton per perlite) (W.R. Grace and Company, 1984). Dryer operation releases an additional 16 kg CO_2 Mg per perlite (32 lb CO_2 ton per perlite) (Ecology Audits Inc., 1979). Combined, these sources produce a total of 436 kg CO_2 Mg per perlite (872 lb CO_2 ton per perlite) produced.

The greenhouse complex used a total of just 45 kg (100 lb) of perlite in 1998, and 68 kg (150 lb) in each of 1999 and 2000. Converting the 'carbon dioxide cost' of this input to production, we estimate that this caused a 19.6 kg (43.2 lb) CO_2 discharge into the atmosphere in 1998 and a 29.6 kg (65.3 lb) CO_2 discharge in each 1999 and 2000 production years (Table 3).

3.5. Seedling container trays and greenhouse coverings

The seedling container trays (Rigi-pots distributed by Stuewe and Sons, Corvallis, OR, USA) were manufactured from high-density polyethylene (HDPE) plastic resin. The greenhouse coverings (clear polyethylene plastic) material was manufactured from linear low-density polyethylene (LLDPE). In contrast to the other inputs to production at this greenhouse facility, both of these polyethylene products represent a dense carbon sink in their final product form. Both HDPE and LLDPE products are approximately 86% by weight composed of carbon atoms in the complex polyethylene molecule (EPA, 2001).

Although various volatile organic compounds (VOCs) are created in the manufacture of polyethylene resins (EPA, 1997; Barlow et al., 1996; EPA, 1983), there are no reported emissions of carbon dioxide from the manufacture process. Barlow et al. (1996) reported that the manufacture process created gaseous and volatile hydrocarbons including heavy hydrocarbons (HHCs), primarily C_4–C_{16} (HDPE: 38.5 g HHC/Mg polyethylene resin; LLDPE: 21.3 g HHC/Mg polyethylene resin) and light hydrocarbons (LHCs) including ethane (HDPE: 0.02 g LHC/Mg polyethylene resin; LLDPE: 0.04 g LHC/Mg polyethylene resin), ethylene (HDPE: 0.01 g LHC/Mg polyethylene resin; LLDPE: 0.02 g LHC/Mg polyethylene resin), and propylene (HDPE: <0.01 g LHC/Mg polyethylene resin; LLDPE: <0.01 g LHC/Mg polyethylene resin).

Because HDPE and LLDPE are 86% by weight composed of carbon, polyethylene resin plastics are not considered a net source of carbon dioxide emissions in the manufacture process, even though some amount of carbon dioxide can be emitted to the atmosphere from combustion equipment used to heat reactors, dryers, and other process equipment used for the container tray and greenhouse covering manufacture process (EPA, 1997). In summary, no carbon emissions to the atmosphere have been attributed to the seedling raising process as a result of the use of polyethylene products.

3.6. Cement used in construction

The Russian Federal Forest Service built two warehouses to accommodate equipment used in support of the greenhouse facilities. The first building is home to seed cleaning, seed sorting, and storage equipment. It is also home to a walk-in freezer (seed storage) and walk-in cooler (seedling winter storage). The second structure contains a seed sowing line, peat moss grinder, winter storage for seedling containers, and a small project office. Both of these buildings required substantial amounts of cement in construction (flooring and foundation).

Energy consumption is the largest single factor contributing to carbon dioxide emissions in the manufacture of cement (EPA, 1995). The carbon dioxide emissions from cement manufacturing are generated by two mechanisms: (1) fuel combustion releases substantial quantities of carbon dioxide, and (2) substantial quantities of carbon dioxide are generated through calcining of limestone or other calcareous material. The calcining process thermally decomposes calcium carbonate ($CaCO_3$) to calcium oxide (CaO) and carbon dioxide (CO_2) (Buildinggreen, 1996). Cement contains approximately 63.5% calcium oxide. About 1.135 units of calcium carbonate are required to produce 1 unit of cement, and the amount of carbon dioxide released in the calcining process is about 500 kg Mg^{-1} (1000 pounds per ton) of cement produced.

When combined, the carbon dioxide emissions total approximately 374 kg CO_2 m^{-3} (629 lb CO_2 yd^{-3}) of cement produced (Buildinggreen, 1996). Each building at the Sosnovka Seed Breeding Center required approximately 144.0 m^3 (188.3 yd^3) of cement for flooring and foundations. Therefore, each building caused the release of approximately 53,856 kg (118,730 lb) CO_2 when built. By placing a useful life of the buildings at 20 years we estimate the average annual carbon dioxide emission equivalent to be 2692.8 kg (5936.5 lb) CO_2 per year per building due to cement usage.

In addition, approximately 11.0 m^3 (14.4 yd^3) of cement were used for footings in the greenhouse foundation representing an emission of 4114.0 kg (9069.7 lb) CO_2 per greenhouse. We estimate the useful life of a greenhouse frame support to be 20 years.

Combining these sources, the 1998 carbon dioxide emission factor, when the center operated two greenhouses and two production buildings, is calculated as $(2 \times 205.7\,\mathrm{kg\,CO_2}) + (2 \times 2692.8\,\mathrm{kg\,CO_2})$ for a total of 5797.0 kg (12,780.0 lb) CO_2. In 1999 and 2000, the center operated three greenhouses bringing the annual emission factor to 6002.7 kg (13,233.5 lb) CO_2 from cement usage (Table 3).

3.7. Steel and iron used in construction

In addition to concrete, the two warehouses were built using steel frames and metal siding. Each building included 34 metric tons (74,956 lb) of steel framing and 14 metric tons (30,864 lb) of metal siding and roofing, for a total steel use of approximately 48.0 metric tons (105,820 lb) each. In addition to being an energy intensive manufacturing process, the production of iron and steel causes the emission of carbon dioxide (EPA, 2001). Iron is approximately 4.0–4.5% carbon by weight, and carbon dioxide is produced during the oxidation process. The steel that is created from this process is less than 1.7% carbon by weight (Worrell et al., 2001). Worrell et al. (2001) further determined that the processes involved in manufacturing primary steel and secondary steel created the average emissions 1.38 kg CO_2/kg final product steel in the USA during 1994.

Unfortunately, there exists no similar assessment of the Russian steel manufacturing sector for any year. The US steel manufacturing industry of 1994 can be used as a proxy for the Russian steel manufacturing industry, recognizing that the actual probable emissions caused from steel manufacture in Russia will be larger due to a greater reliance on coal for electricity generation (Kalashnikov, 1997) and fewer efficiencies in the manufacture process of iron products (Royal and Pardum, 1998), due, in large part, to the historically monopolistic, state-enterprise structure of the industry (Kelly, 2000).

Based on the 1994 US carbon dioxide emissions rate of 1.38 kg CO_2/kg steel, each building used at the Sosnovka Seed Breeding Center caused the emissions of approximately 66,240 kg CO_2 ($1.38\,\mathrm{kg\,CO_2} \times 48,000\,\mathrm{kg}$ steel) (146,032 lb CO_2) during their construction. Combined, this totals 132,480 kg CO_2 (292,064 lb CO_2) for both buildings. By placing a useful life of the buildings at 20 years we estimate the average annual carbon dioxide emission factor to be 6624.0 kg (14,603.2 lb) CO_2 per year for both buildings due to processed steel usage (Table 3).

In the calculations concerning building construction (cement and steel) we are assuming that carbon should be counted at full value whenever it is emitted or stored. However, since the framework for the current study counts annual emissions, some way must be found for reconciling the once every 20-year carbon emissions for building construction with the annual emissions related to other inputs. Counting emissions at either the once-in-20-years construction related emissions or at zero for non-construction years would misrepresent these emissions. Instead, we prorated the emissions over the 20-year life of the project. One might think of it as if one were undertaking 20 identical projects, with each project starting one year apart. An alternative approach might involve discounting future carbon emissions to the atmosphere or placing a premium on current carbon sequestration (depending on timing). Whether time should matter and how time should be treated in these calculations is clearly an important issue, but it is beyond the scope of the present paper. In summary, for this study the carbon dioxide released to the atmosphere was allocated to the seedlings over the useful life of the structures, even though all of the carbon dioxide emissions were observed in the year of construction. Fig. 3 presents the emission flow volumes graphically: (1) showing the emissions and sequestration as they occur (block charts); and (2) showing the allocation of emissions to seedlings, prorated over the useful life of the structures (line chart).

3.8. Total carbon dioxide emissions from all sources

Actual emissions of carbon dioxide during the initial construction phase of the center totaled 240,192 kg (529,524 lb) CO_2 from cement and steel manufacture (Fig. 3). Additional carbon dioxide emissions from cement usage in construction occurred in 1998 (8228 kg–18,139 lb) and 1999 (4114 kg–9070 lb). Annual emissions of carbon dioxide caused by facility operations equaled just 34,114.4 kg

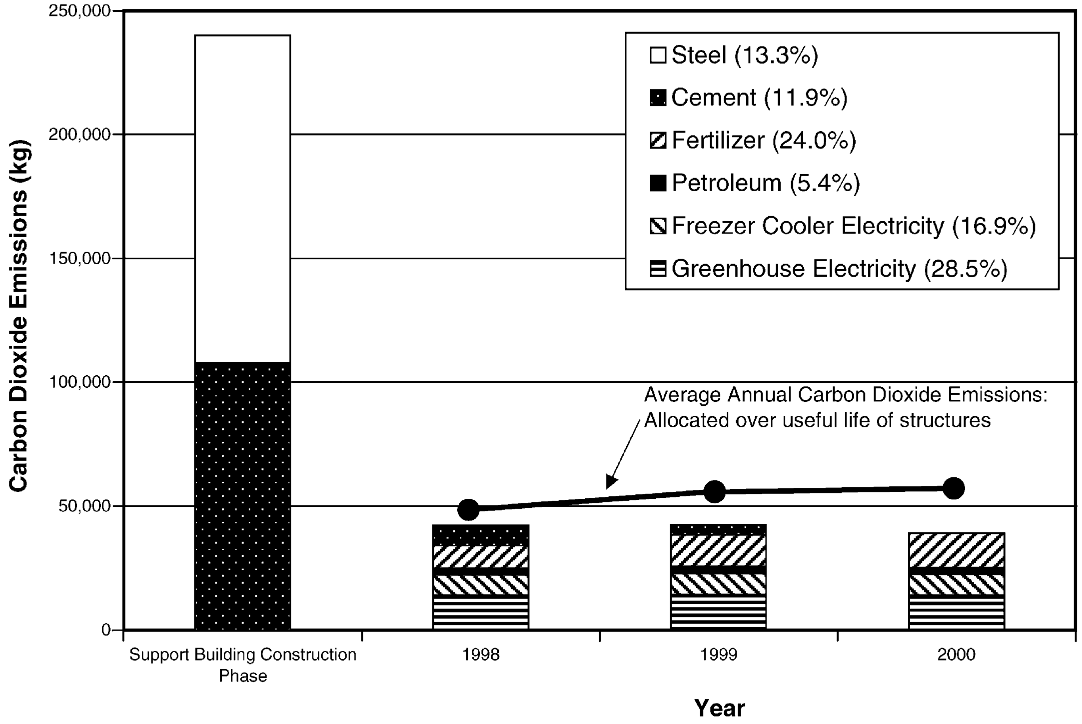

Fig. 3. Carbon dioxide emissions by source.

(75,208 lb) in 1998; 38,508.1 kg (84,894.4 lb) in 1999; and 39,061.6 kg (86,114.6 lb) in 2000 (Fig. 3).

In order to allocate carbon dioxide emissions from construction to the outputs of the process (seedlings), we propose to distribute the carbon dioxide emissions that occurred during construction over the useful life of the structures as discussed above. By apportioning one time emissions over the structure's useful life, and then to the volume of seedlings grown each year, we derive the 'fixed carbon cost' attributable to the seedlings, expressed on a per-seedling-per-year basis. The annual 'variable carbon cost' is added to this sum to create the actual carbon emissions cost of raising the seedlings.

Following this procedure, the total allocated emissions to the atmosphere equaled approximately 46,555.0 kg (102,634.5 lb) CO_2 in 1998; 51,164.4 kg (112,796.3 lb) CO_2 in 1999; and 51,717.9 kg (114,016.5 lb) CO_2 in 2000 (Fig. 3 and Table 4). When considered in light of annual production, the 'initial carbon outlay' was approximately 93.1 g (3.28 oz) per seedling in 1998; 73.1 g (2.58 oz) per seedling in 1999; and 68.4 g (2.41 oz) per seedling in 2000. The 3-year-weighted average 'initial carbon outlay' was

Table 4
Annual seedling production and grams of carbon released to the atmosphere in support of the greenhouse facility

Year	CO_2 release (kg)	Number of seedlings raised	g CO_2/seedling (g)	Equivalent g C/seedling (g)
1998	46,555.0	500,000	93.1	25.4
1999	51,164.4	700,000	73.1	19.9
2000	51,717.9	755,700	68.4	18.7
All years	149,437.3 (total)	1,955,700 (total)	76.4 (weighted average)	20.8 (weighted average)

approximately 76.4 g (2.69 oz) per seedling. This can be considered the average carbon dioxide emissions cost of raising conifer seedlings at this facility.

There would appear to be a decreasing trend of average annual carbon dioxide emissions in that the average annual carbon cost per tree decreased each year, over the 3-year period. This has occurred because of allocating fixed carbon costs over the total number of seedlings. Thus, energy costs, such as electricity required for the freezer-and-cooler operations, and the cement and steel used for the construction of the support buildings remained the same as operations expanded. Both the refrigeration complex and the support buildings operated with excess capacity in 1998, and to a lesser extent even in 1999 and 2000. Since seedling production increased each year, these fixed costs were allocated among an increasing number of seedlings and the average declined. In economic terms these declining average carbon emissions are ‘returns to size’ of the operations. We would not expect to see this average annual carbon emission cost continue to decrease past 2000 unless additional greenhouses are built.

3.9. Carbon sequestered by the seedlings

There was no significant statistical difference ($P = 0.8973$) between the ODW of the 95 ml and the 110 ml container-grown larch seedlings (Table 5). There was a significant difference between the ODW of the 70 ml container-grown seedlings and the ODW of the other two groups, individually at the 90% confidence interval. One greenhouse, occupied by 110 ml seedling containers, was covered with a low quality plastic (non-polyethelene resin composite). The other greenhouses were covered with a 6 mil polyethelene greenhouse clear film (3-year), specially manufactured for greenhouse purposes (LLDPE). This factor probably contributed to the lower than expected ODW of the seedlings from the 110 ml containers.

While determining the percent composition of carbon in the seedlings, six of the 22 samples displayed peak voltages that were less than 0.5 V during mass spectrometry testing. The Idaho Stable Isotopes Laboratory requires a voltage peak of 1.0 V or more on each sample to insure accuracy of the results during an evaluation. Since that criteria was not met, these six sample results were discarded from the sample set leaving 16 accurate samples.

The average carbon content of the seedlings was $43.4 \pm 6.7\%$. There was no statistical difference between carbon content of the seedlings raised in the greenhouses covered with polyethelene plastic versus non-polyethelene plastic, nor was there any statistical difference in the carbon content between the seedlings raised in the three different container sizes ($P = 0.90$).

By considering the three container sizes that were used for raising *L. gmelinii* at the Nekrasovka greenhouse in the year 2000, we can determine the quantity of carbon sequestered by the tree seedlings. First, the 70 ml seedling containers produced seedlings with an average ODW of 0.88 ± 0.198 g. At $43.4 \pm 6.7\%$ carbon by weight, these seedlings possessed, on average, 0.3816 ± 0.0337 g carbon each. The seedlings raised in the 95 ml containers possessed an average ODW of 1.21 ± 0.381 g, for an average per seedling carbon content of 0.5247 ± 0.0595 g. Finally, the seedlings raised in the 110 ml containers grew to an average ODW of 1.19 ± 0.513 g, for an average carbon content per seedling of 0.5160 ± 0.0780 g (Table 5).

3.10. Payback period

During the 3 years covered in the evaluation at this greenhouse complex, a total of almost 2.0 million

Table 5
Seedling data from *L. gmelinii* raised in 2000 at the Nekrasovka Greenhouse Facility

Container size (ml)	Height above root (cm)	Root depth (cm)	Stem caliper (mm)	Winter storage weight (g)	ODW, total grams (standard deviation)	Carbon in plant fiber at 43.4%, total grams (standard deviation)
70	23.93	7.36	2.33	0.94	0.88 (0.198)	0.3816 (0.0337)
95	37.16	9.22	2.60	1.30	1.21 (0.381)	0.5247 (0.0595)
110	35.55	11.33	2.54	1.29	1.19 (0.513)	0.5160 (0.0780)

seedlings were raised (mostly larch) resulting in the release of approximately 149,437.3 kg (329,447.3 lb) CO_2 attributable to those years of production. When averaged over the 3 years of seedling production (all species), each seedling represents an average release to the atmosphere of 76.4 g (2.69 oz) CO_2. Since the carbon dioxide molecule is made up of one carbon atom (12 g mole^{-1}) and two oxygen atoms (32 g mole^{-1}), the actual magnitude of carbon emissions to the atmosphere from 76.4 g CO_2 per seedling is, on average, approximately 20.8 g (0.73 oz) C per seedling. This is the amount of carbon that each larch seedling, must sequester from the atmosphere in order to 'break even' on a carbon budget from greenhouse production (pre-planting).

On average, each larch seedling at this greenhouse complex raised in 95 and 110 ml seedling containers has sequestered 0.5210 ± 0.0504 g of C. Considering the average per seedling carbon emission contribution of 20.8 g C, these seedlings represent a net carbon cost of approximately 20.3 g (0.72 oz) C per seedling. In other words, each seedling must sequester an additional 20.3 g C per tree in order to 'pay back' the carbon costs attributable to raising the seedling in these greenhouses. Sequestration versus emission can be expressed as a ratio of 1:40. For each unit of carbon sequestered by seedlings during this 3-year sample period, this greenhouse complex typically caused 40 units of carbon emissions to the atmosphere.

Pellicer et al. (2000) determined that the total carbon concentration of *L. eurolepis* (European regions of the former Soviet Union) cuttings did not change with time, although nitrogen reserves did. Assuming the same is true for *L. gmelinii*, we conclude that the total ODW of each tree must reach 47.9 g (20.8 g per tree/43.4%) to equal the break-even point where carbon dioxide emissions at the greenhouse equal carbon sequestration by the individual seedlings (not adding the addition carbon emission producing management activities that will occur in the intervening years). Brown (1978) observed that converting green weight to ODW for various softwood species averaged approximately 50% moisture on small-diameter trees. This conversion was not in disagreement with conversions observed for the seedlings raised at this greenhouse complex. With this in mind, total live tree weight would have to exceed 95.8 g (3.38 oz) to sequester 20.8 g C.

Published data on the biomass accumulation of softwoods in the Russian Far East during the first 10 years after planting are not available. However, data are available for trees under 4.57 m (15.0 ft) indigenous to the Northern Rocky Mountains of the USA, including larch species (Brown, 1978). Distinct genetic differences exist between these North American larch species and Russia's *L. gmelinii* based on variations at isozyme loci (Whitlock, 1995; Semerikov and Lascoux, 1999). However, despite the spatial and temporal separation, similar environmental conditions have led to low levels of genetic variation between certain species of Larix, such as that found between *L. occidentalis* (Nutt.) and *L. lyallii* (Parl.) (A. Henry) with *L. gmelinii* (Semerikov and Lascoux, 1999). This notwithstanding, the whole tree weight predictions of Brown (1978) can be used with caution, recognizing the need for further research in this area (Eq. (5)):

$$W = e^{-3.720+2.411\ln h} \tag{5}$$

where 'W' is the whole tree weight (green) (in lb); 'h' the tree height (in ft); 'e' and 'ln' are natural log functions and $R^2 = 0.87$ with the MSR $= 3.109$ for trees less than 4.57 m (15 ft) in height.

Rearranging to express as a function of tree height (h)

$$h = e^{(\ln w+3.720)/2.411} \tag{6}$$

By inserting the targeted 'break-even' green-weight as 0.211 lb (95.8 g) for 'w' in Eq. (6) we can estimate the total tree height needed for our seedlings to sequester the 'break-even' 20.8 g C used to grow them as 74.68 cm (2.45 ft).

Although early tree biomass growth estimates for the Russian Far East are scarce, anecdotal evidence, observations, and discussions with working foresters in Khabarovskii krai indicate that moderate to highly productive forest sites in the region could supply this amount of tree growth after three growing seasons providing competition is eliminated prior to planting. However, on low-productivity sites, especially where persistent permafrost conditions exist, this amount of tree height growth may take as long as 10 years to attain, especially if competition from shrubs and grasses is present, or if animal damage is an issue.

4. Discussion

This study measures carbon emissions for one aspect of forest management in one location. However, its results should be useful as an indicator of the general magnitude of the seedling nursery phase of forest management in the Russian Boreal forest. Application of our research procedures to other geographical regions would need to account for differences in greenhouse gas emissions from differing practices. For instance, approximately 45.4% of the total carbon dioxide emissions brought about by raising these tree seedlings were caused by the burning of coal to produce electricity. At first glance, it would seem that this factor would be less significant in regions that acquire electricity from hydroelectric power. However, Rudd et al. (1993) point out that bacterial decomposition of flooded forest biomass in hydroelectric reservoirs produce significant amounts of carbon dioxide and methane from both aerobic and anaerobic decomposition. These greenhouse gas emissions may be comparable to emissions from fossil fuel power plants. While other authors disagree with the magnitude of their findings and the pattern of greenhouse gas emissions (especially from methane) (Gagnon and Chamberland, 1993; Svensson and Ericson, 1993; Rosa and Schaeffer, 1994), there is agreement that greenhouse gas emissions from hydroelectric reservoirs are far from negligible.

The second largest source of carbon dioxide emissions in raising greenhouse seedlings at this complex was from natural gas combustion in the process of manufacturing fertilizers and perlite. Approximately 24.0% of total carbon dioxide emissions were from fertilizer manufacture and only 0.1% from perlite manufacture. It is unlikely that this factor will be significantly different in other locations since this facility has procured its fertilizers and perlite from North America and Europe in the past.

Cement usage at this facility accounted for approximately 11.9% of total carbon dioxide emissions while steel used in building construction accounted for 13.3%, when allocated over the useful life of the structures. This allocation methodology is logical but it does not follow the actual pattern of greenhouse gas emissions at least for a one-time project. In our study we have apportioned total carbon dioxide emissions over the useful life of the structures by averaging the total carbon dioxide emissions over the life of the project. However, most of the carbon dioxide emissions were actually released over a much shorter time period; the period of initial construction (Fig. 3).

Petroleum usage at this facility accounted for only 5.4% of total carbon dioxide emissions from production inputs. Energy efficiency of vehicles at this facility most likely contributed to a slightly higher usage than otherwise might be expected at a similar facility in North America or Europe because the age of the machines was considerable. Newer motors and more efficient designs would lead to higher fuel efficiency and therefore less carbon dioxide emissions during the production of seedlings.

Other potential sources of carbon dioxide emissions were not included in this study (Table 1). Further research into this area should quantify the magnitude and significance of these sources. These factors raise the issue of what indirect carbon emissions should be counted and which should not. We have used the guideline that carbon should be attributed to the project if its emission would not have occurred but for the existence of the project. By this reasoning, for example, we do not count the carbon used to support the laborers living, as these activities would have occurred regardless of whether or not the seedlings were raised in a greenhouse.

In terms of national policy and implications of tree planting efforts in various countries, these results have far-reaching implications. Although many policy makers and policy specialists advocate tree planting as a net carbon sequestration event, we must consider the temporal impacts of a national reforestation program in the Russian Federation and other forestation programs elsewhere. In the short term, a containerized greenhouse-based reforestation program will cause a net carbon dioxide emission increase to the atmosphere that will not be offset immediately through increased carbon sequestration by the seedlings. In the longer term, a containerized greenhouse-based reforestation program for the Russian Federation should result in increased net carbon sequestration. If carbon sequestration in forests is to be an important tool in addressing world climate change concerns, more studies like this are needed to understand when and by how much net carbon sequestration occurs.

The general approach used in this paper must be broadened and widely replicated if we are to understand and quantify the net carbon balance for forestation activities. Other studies are needed to capture carbon emissions of, e.g., management activities at other stages of the tree lifecycle. Still, carbon relevant management activities are likely to occur during the nursery and planting stages of forestation, in which case this study captures most of the relevant typical carbon emissions. However, the figures produced in this study are based on particular circumstances and assumptions. A number of factors will determine how representative these figures may be.

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