An analysis of greenhouse gas emissions from the production of commercial fertilizers, in relation to their use in carbon-sequestration reforestation projects.

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ABSTRACT

This paper aims to analyze the environmental impact of greenhouse gas emissions from the production of commercial fertilizers, in relation to their use in carbon-sequestration reforestation projects. It will look at the emissions related to the production and application of fertilizers. It will also analyze the benefits of the use of fertilizers for seedlings and near-end of rotation stands. Finally, the results will be discussed in terms of net carbon storage effects, and any possible implications for landowners looking to make decisions regarding carbon sequestration projects.

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Introduction

The Kyoto Protocol currently recognize seven land-use, land use change, and forestry activities, including forest management, afforestation, reforestation, and (avoided) deforestation. As a result, many landowners are seeing carbon sequestration projects as a viable source of capital and investment for the managing of their lands. These various plantations and forest land vary significantly in the management practices, maintenance and implementation practices, and natural productivity, and thus each require different management strategies to maximize future benefits for yields, carbon storage, or whatever the long-term goals and values may be.

For those interested in carbon sequestration projects, enhanced forest management practices, include fertilization, are recommended in cases where such actions can make forest ecosystems more resilient to climate-induced stresses (T. Andrew Black et al., *Carbon Sequestration in British Columbia's Forests and Management Options*, November 2008).

In the past, forest carbon assessments have focused primarily on changes in biomass carbon as a result of management activities, while assuming that greenhouse gas (GHG) emissions from direct and indirect forestry activities themselves are minimal (Edie Sonne, *Greenhouse Gas Emissions from Forestry Operations: A Life Cycle Assessment,* July 2006). This assumption can not only result in the omission of potentially significant emission factors during the accounting process, but also inhibits the decision making process for landowners evaluating alternative land management practices (Sonne, 2006). Because of this, it is essential to quantify the direct and indirect carbon costs of various forest management practices in consideration of their effect on other ecosystem goods and services (Black et al., 2008).

Fertilization can be an effective means of increasing the merchantable yield and value of established forests. On nutrient-limited sites, fertilizers can improve the growth of individual stands (MOF, Forest Fertilization Guidebook, September 1995). In addition, fertilization can be effective in improving select nursery stock. Particularly in the early stages of tree improvement work, the select nursery stocks will be much more valuable than bed-run or run-of-the-woods seedlings (T.E. Maki, *The Place of Fertilizers in Forest Tree Improvement*, 1959).

Fertilizers are used commonly in agriculture, and with the growing population of the earth demanding more and more food every day, fertilizers are among the most important element to secure sufficient food production (Tore K. Jenssen, *Energy Consumption and Greenhouse Gas Emissions in Fertilizer Production,* Amendment, April 2003). However, this does not mean that neither the industry nor the user to discount the unintended consequences and effects of its production or use (IFA, 2010).

Benefits and Usage of Fertilizer

Fertilizers are commonly used to accelerate stand development, but are equally useful to facilitate the rehabilitation of previously disturbed sites (MOF, 1995). The use of slow release fertilizers can be useful in establishing stands at the time of planting, particularly on sites where nutrient availability is a limiting factor. In addition, fertilizing can greatly aid in management objectives where rapid early growth is needed to either meet forest level objectives, or to allow the seedlings to establish themselves above surrounding vegetative competition (MOF, 1995). For example, in seed orchard establishment, there is a desire to grow clones to seed-bearing size as efficiently as possible, in order to produce a vigorous growth of understock in advance of the grafting program (Maki, 1959).

An additional benefit both practical and economic, to the application of a fertilizer to seedlings at the time of planting is the potential elimination of visits to the planting site in the future (MOF, 1995). This, however, may be less relevant for carbon-based forest management projects, where there is a constant need for auditing and verification due to the large values at stake.

According to a study presented by Gunnar Kongshaug at the IFA Technical Conference in Marrakesh, Morocco 1998, fertilizer production consumes approximately 1.2% of the world's energy and is responsible for 1.2% of the total Greenhouse gas emissions (Gunnar Kongshaug, *Energy Consumption and Greenhouse Gas Emissions in Fertilizer Production*, 1998).

Case Study: Seedling response of three agroforestry tree species to phosphorous fertilizer application in Bangladesh

The Journal of Forestry Research (2009) published a study of seedling response to phosphorous fertilizer application to three agroforestry tree species, conducted in Bangladesh to determine the effect on growth and nodulation capabilities (Uddin 2009). In the study, triple super phosphate (TSP) fertilizer [Ca(H2PO4)2; containing 48% of P2O5] was applied @ 80kg/ha to 6-month old seedlings of Albizia chinensis, Albizia saman, and Pongamia pinnta in nursery beds in Bangladesh. These fertilized seedlings were compared to seedlings in unfertilized beds, and it was revealed that seedling growth was enhanced significantly with the application of P-fertilizer. The study also suggested that in terms of nodule number and size there was a significant increase as a result of the P-fertilization (Uddin 2009).

*The results for the study can be found in tables 1 and 2 in appendix 1.

The results of the experiment showed that the application of P-fertilizer to the seedlings significantly enhanced the seedling growth of select species in nursery conditions (Uddin 2009). The overall growth rates of the selected species were increased in most cases, and the study concluded that growth was more as P-fertilizer was applied.

Result is unsurprising, as low soil fertility is one of the greatest biophysical constraints to agroforestry production (Ajayi 2007). This is particularly true in tropical areas where phosphorous can be the most common limiting nutrient, as it plays an essential role in plant nutrition and energy transfer (Ackerson 1985).

Emissions from Production and Practice

Upstream vs. Downstream Emissions

The Greenhouse Gas Protocol separates emissions into direct ("emissions from sources that are controlled by the company") and indirect ("emissions that are a consequence of the activities of the company but occur at sources owned or controlled by another company (World Resources Institute, 2004). As an example, during fertilization, N20 is emitted due to nitrogen fertilization (direct) and CO2 is emitted during combustion of diesel or jet fuel (indirect), depending on the application process.

Theses direct and indirect emissions are example of downstream emissions, as oppose to upstream emissions from the production and transport of the fertilizers. While a landowner is likely to be only responsible and/or get credit for on-site direct changes in emissions, it is still important to understand the complete ramifications of the landowner's decision (Sonne 2006).

Upstream Emissions from Production

The most common types of fertilizers in commercial production are Nitrogen-containing and Phosphate Fertilizers. For emissions associated with nitrogen-containing fertilizer production, carbon dioxide (CO2) emitted from natural gas combustion during ammonia synthesis, and nitrous oxide (N2O) emissions from nitric acid production (Wood and Cowie, 2004) are the key components. In addition, the production of methane (CH4) is also of great concern in terms of climate change perspectives.

In production, emissions may arise during the extraction, transport, and fertilizer production phase. In addition, the production phase requires a great deal of energy, and the GHG emissions from production are closely associated with energy consumption

(Wood and Cowie, 2004). Kongshaug (1998) estimates that fertilizer production consumes approximately 1.2% of the world's energy.

The main energy requirement for production of fertilizers is linked to the nitrogen component; 94% for N, 3% for P2O5, and 3% for the K2o component on a global basis (Tore, 2003). Early oil and coal based ammonia plants could consume in the order of 50-60 GJ/tonne N. In 2003, a common ammonia plant consumed approximately 34.5GJ / tonne N, and produced 1.97 tonnes CO2/ tonne N (Tore, 2003).

Nitrogen Fertilizer Production

Emissions factors for the following key nitrogen fertilizers and their intermediate products are of concern:

1. Ammonia (intermediate)
2. Nitric Acid (intermediate)
3. Ammonium Nitrate (AN), Calcium Ammonium Nitrate (CAN), and "Mean Nitrogen Fertilizer" (Wood and Cowie, 2004)
4. Urea and Urea Ammonium Nitrate (UAN)

1. Ammonia

Ammonia (NH3) is the primary input for the majority of worldwide nitrogen fertilizer production (DOE 2000; EFMA 2000a, Wood and Cowie 2004). The CO2 emissions from the production of ammonia account for the majority of emission resulting from nitrogen fertilizer manufacturing (Wood and Cowie, 2004).

Production Overview

- NH3 is synthesized from a hydrogen and nitrogen mixture at an elevated temperature and pressure.
- Nitrogen is obtained from the air, Hydrogen from either steam reforming of natural gas (or other light hydrocarbons) or partial oxidation of heavy fuel oil or coal (Wood and Cowie, 2004).
- About 85% of the world's ammonia production is based on steam reform (EFMA 2000a).
- About 80% of the world's ammonia production uses natural gas for steam reforming (EFMA 2000a).
- Ammonia synthesis consumes around 25-35 GJ/tonnes of ammonia through steam reforming (Wood and Cowie 2004; Kongshaug 1998; DOE 2000).
- As a result of the energy required, CO2 emissions are the major component of GHG budgets for ammonia manufacturing (Wood and Cowie 2004).

*Table 3 in appendix 2 summarizes greenhouse gas emission factors for Ammonia Production.

2. Nitric Acid

Nitric Acid is an intermediate product in fertilizer manufacturing used in the production of Ammonium nitrate, Calcium nitrate, and Potassium Nitrate, which can be used as independent or compound fertilizers (Wood and Cowie 2004).

Production Overview

- Most Nitric Acid is produced by catalytic oxidation of ammonia at high pressures and temperature (Wood and Cowie, 2004).
- This produced Nitrous Oxide (NO2), which undergoes oxidation to nitrogen dioxide.

- The Nitrogen dioxide is then absorbed in water yielding a nitric acid solution (EFMA 200b).
- Nitrous oxide (N2O), nitrogen monoxide (NO, nitric oxide), and nitrogen dioxide (NO2) are all produced as by-products from the oxidation of ammonia (EFMA 2000b).
- The exothermic reaction from ammonia to nitric acid contributes a net steam export (Wood and Cowie 2004).**

Nitrous oxide (N2O) is the most significant GHG emitted from nitric acid production. It is deemed a highly "effective" greenhouse gas, with a global warming potential 310 times greater than CO2 (IPCC 1996a).

*Table 4 in appendix 2 summarizes greenhouse gas emission factors for Nitric Acid production.

**Steam Credits

Many reactions along the production cycle of these fertilizers produce exothermic reactions and thus can create a net export of steam. This net export can be used to warrant emissions credits for the manufacturing process, or in-fact replace the combustion of fossil fuels elsewhere in the life cycle (Wood and Cowie 2004).

3. Ammonium Nitrate (AN), Calcium Ammonium Nitrate (CAN) and "Mean Nitrogen Fertilizer" (N fertilizer)

Ammonium Nitrate is used commonly as a nitrogenous fertilizer across the world (EFMA 2000c, DOE 2000, Wood and Cowie 2004). Calcium ammonium nitrate is a derivative of ammonium nitrate and is a particularly important fertilizer in Europe (Wood and Cowie 2004). "Mean Nitrogen Fertilizer" refers to a range of different common

fertilizer types (Wood and Cowie 2004).

Production Overview

- Gaseous ammonia is neutralized with aqueous nitric acid.
- The solution is evaporated and formed into solid fertilizer in a granulation phase (EFMA 2000c) to produce Ammonium Nitrate.
- Mixing AN with dolomite or limestone produces CAN (EFMA 2000c).

N_2O emissions from nitric acid production account for 60-78% of AN/CAN production CO_2e emissions, and 52-61% of Mean Fertilizer production CO_2e emissions (Wood and Cowie 2004).

*Table 5 in appendix 2 summarizes greenhouse gas emission factors for Ammonium Nitrate, Calcium Ammonium Nitrate, and "Mean Nitrogen Fertilizer" production.

4. Urea and Urea-Ammonium Nitrate

Urea accounts for nearly 50% of world nitrogen fertilizer production (UNEP 1996).

Production Overview

- Ammonia and Carbon dioxide are combined at high pressure to form ammonium carbonate (Wood and Cowie 2004).
- The Ammonium carbonate is heated and dehydrated to from urea and water (EFMA 2000d).
- Liquid UAN is formed by mixing and cooling urea and ammonium nitrate solutions (EFMA 2000d).

CO2 emissions during ammonia synthesis contribute to the majority of emissions from urea production. N2O emissions from nitric acid as an intermediate product of ammonium nitrate syntheses also accounts for a significant proportion of emissions from UAN production (Wood and Cowie 2004).

Phosphate Fertilizer Production

Emissions factors for the following key phosphate fertilizers are of concern:

1. Single Superphosphate (SSP)
2. Triple Superphosphate (TSP)
3. Diammonium Phosphate (DAP)
4. Monoammonium Phosphate (MAP)
5. "Mean Phophate Fertilizer"

Phosphate fertilizers are based on phosphoric acid (Kongshaug 1998), and are produced from various combinations of phosphate rock, sulphuric acid, phosphoric acid, and ammonia (Wood and Cowie 2004):

Production Overview

- SSP = phosphate rock and sulphuric acid
- TSP = phosphate rock and phosphoric acid
- DAP/MAP = phosphoric acid and ammonia
- Phosphoric acid is produced when sulphuric acid is reacted with naturally occurring phosphate rock (EFMA 2000f, DOE 2000).

- More sulphuric acid is produced than any other chemical in the world, with the largest single user being the fertilizer industry (EFMA 2000e).

Sulphuric acid is required for production of phosphoric acid. It is a key chemical for the production of 80% of the world's phosphate fertilizers (Torre, 2003). Emissions estimates relating to the consumption of fossil fuels as an energy source for the various production processes are largely dominated by CO2. The net emissions are largely determined by the method of sulphuric acid production (Wood and Cowie 2004).

Figure 1 and Tables 8 in Appendix 4 show a summary of fertilizer building blocks, their associated nutrient contents, and their accumulated energy consumption (from Torre 2003 and Kongshaug 1998).

Downstream Emissions from Application and Practice

As stated at near the beginning of this paper, forest carbon assessments have focused primarily on changes in biomass carbon as a result of management activities, while assuming that greenhouse gas (GHG) emissions from direct and indirect forestry activities themselves are minimal. In the following Case study, Edie Sonne (2006) conducted a study of forest activities to confirm or deny the claim that greenhouse gas (GHG) emissions from forest activities are minimal in regards to forest carbon assessments. Sonne used the building block method adopted from Kongshaug (1998) to calculate emissions from fertilizer production, based on nitrogen, phosphorus, and potassium contents and forms, and estimated data for pesticides, fertilizers, and transportation to storage from Ecoinvent Data Version 1.1 (Frischknecht and Jungbluth, 2004).

Edie Sonne's study constructed gas emissions budgets for 408 "management regimes" regarding the direct and indirect emissions from Pacific Northwest (PNW) Douglas-fir (*Pseudotsuga menziesii (Mirbel) Franco*) using Life Cycle Assessment (LCA) methodology. The management regimes were constructed using 3 seedling types, 2 site preparation methods, and 17 combinations of management intensity including

fertilization, herbicide application, precommercial and commercial thinning, and no treatment, as well as 4 different rotation ages (30, 40, 50, and 60yrs) (Sonne 2006).

The functional unit of the study was 1ha of forestland managed for 50yrs (Sonne 2006). The results are quantified into Greenhouse gas emissions per 100m3 of harvested timber volume, as well as on a per-hectare basis. Both a volume and area based approach are used in the study to avoid a discrepancy occurring as a result of the regimes with larger GHG emissions (i.e. more intensive forest management practices) yielding more volume (Sonne 2006).

Summary of data collections and analyses (Sonne 2006):

The direct and indirect emissions from various life cycle stages of managed forest stand rotation in individual components as determined by Sonne's study were:

Table 8: Direct and Indirect Emission sources from forest activities (Sonne 2006)		
	Emission	
Input	**Direct**	**Indirect**
Seedling Production		
Fertilizer	N2O, NOx, NH3	CO2, NOx, CO
Herbicide		CO2, NOx, CO
Fungicide		CO2, NOx, CO
Electricity		CO2, CH4, NOx, CO
Site Prep		
Herbicide		CO2, CH4, NOx, CO
Dead wood + fuel	CH4, NOx, CO	CO2, CH4, NOx, CO
Transportation to field		
Fuel	CO2, NOx, CO	CO2, NOx, CO
Growth Enhancements		
Fertilizer application	CO, N2O, NOx, CO2	CO2, NOx, CO

Herbicide		CO2, NOx, CO
Fuel for harvesting (thinning)	CH4, CO, N2O, NOx, CO2	CO2, CH4, NOx, CO
Harvesting		
Fuel	CO2, CH4, N2O, NOx, CO	CO2, CH4, NOx, COs
From Sonne (2006)		

The direct emissions from fertilization in seedling production were N2O, NOx, and NH3; the indirect emissions were CO2, NOx, CO. The direct emissions from fertilizer application during the rotation were CO, N2O, NOx, and CO2; the indirect emissions were CO2, NOx, and CO (table 8).

In the study, Carbon dioxide was the largest contributor of GHG emissions from management practices at two-thirds or 67%, N2O at 23%, and CH4 at 10% (table 9).

Table 9: Contributions of each GHG to total impact from Sonne 2006						
	Total emissions			**Direct emissions only**		
Rotation age	CO2	N2O	CH4	CO2	N2O	CH4
Yr	**%**					
30	57	31	12	51	36	13
40	66	24	10	62	28	10
50	72	19	8	74	20	6
60	73	19	8	70	23	8
Average	67	23	10	64	27	9
From Sonne (2006)						

For the direct emissions, we see that the nitrous oxide emissions increased to 27% of the total GEG contribution. This increase is attributed to the anthropogenic N2O emissions resulting from nitrogen fertilization (Sonne 2006). This implies that the biggest

emissions factor during the application process is due to the release of N2O emissions on-site during the first year after fertilization.

Direct emissions for the study, normalized to 50yrs, averaged 8.6 megagrams (Mg) of carbon dioxide equivalents (CO2e) /ha, which accounted for 84% of the total GHG emissions from the average of the 408 regimes.

Harvesting contributed to the most emissions, (5.9MG per 700m3 harvested), followed by pile and burn site prep (4.0Mg CO2e /ha or 32%), and then thirdly fertilization (1.9Mg CO2e / ha or 15%) (Sonne 2006) (table 10).

Table 10: Contribution of each forest activity to overall GHG emissions (Sonne 2006)		
	GHG emissions	**Percent Contribution**
	Mg CO2e /ha /yr	**%**
Seedlings	0.05	<1
Pile and burn	4.0	32
Chemical site prep	0.12	1
Transportation (seedlings)	0.05	<1
Trans (large plug seedlings)	0.15	1
Fertilization	1.9	15
Herbicide Treatment	0.15	1
Harvesting	5.9	51
From Sonne (2006)		

Table 10 reveals that seedling production and transportation contributed less than 1% of the total GHG emissions when assessed on a per-hectare basis (Sonne 2006).

On average, the stands that were fertilized emitted 2.5 Mg CO2e / ha more over their rotation age (figure 2). The discrepancy of the contribution of fertilizer production and application (1.9MG CO2e/ha) and the average normalized difference in the rotations in figure 2 may be a result of an increase in yield, which may lead to higher fuel emissions to run the harvesting machinery (Johnson et al., 2002).
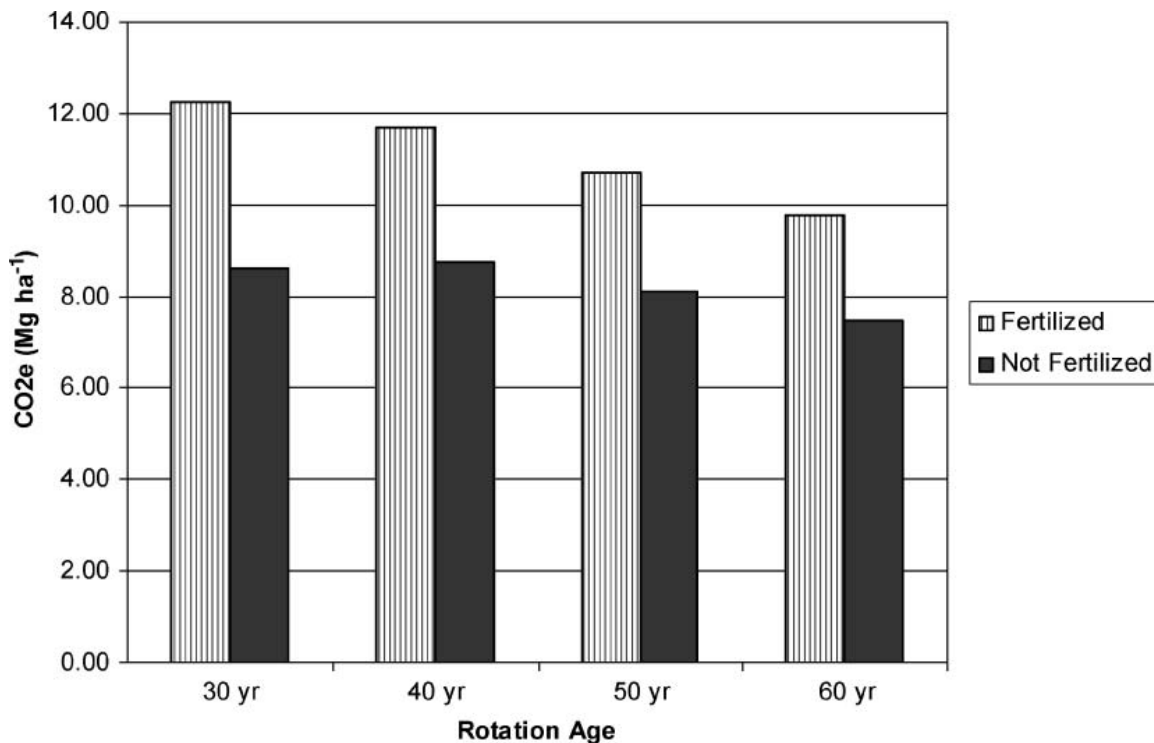
Figure 2: Normalization of GHG impact on fertilized stands by rotation normalized to 50 yr (per ha) (From Sonne 2006)

Figure 2 above shows normalized results from the study revealing the emissions of the fertilized and non-fertilized stands, when analyzed on a per-hectare basis (Sonne 2006). This appears to be a much larger discrepancy than previously seen, however it is important to remember that many of the fertilized stands produce greater volumes of timber, and thus the difference in CO2e (Mg /100m3) is significantly less.

30% of the 1.9Mg CO2e/ha for the fertilization Greenhouse gas emissions are upstream emissions resulting from production and transport. Fertilizer production is

highly energy intensive and can generate considerable Greenhouse gas emissions, primarily from CO2 from ammonia production, and NO2 from nitric acid production (Wood and Cowie, 2004). Thus:

1900kg CO2e * .30 = 570kg CO2e /ha /yr from production

1900 kg CO2e *.70 = 1330kg CO2e /ha /yr from application.

Emissions as part of Carbon Storage

Seedlings

The average Carbon Storage for the Sonne 2006 analysis is defined as the average amount of carbon stored per acre for each management regime, calculated by averaging the carbon storage in 5-yr increments. By comparing the results with the determined average carbon storage of each of the 408 regimes, Sonne calculated that the GHG emissions from forest activities accounted for an average of 4.5% of on-site average carbon storage (Sonne 2006). This varied with rotation age, with the earlier rotation ages producing a higher percentage of emissions to sequestration and the later rotations producing a lesser amount. This result is likely due to additional C storage occurring in the form of woody growth in later years.

Table 11 summarized Sonne's results in terms of GHG emissions to average carbon storage by rotation age (Sonne 2006):

Table 11: Percent of GHG emissions to average carbon storage (Sonne 2006)		
Rotation age	**GHG emissions as % of Carbon storage**	**GHG emissions (incl. transportation) as % of average carbon storage**
Yr	**%**	
30	6.8	12.5

40	4.7	10.6
50	3.8	8.6
60	2.5	6.0
From Sonne (2006)		

We can see that as the rotation age is increased, the amount of emissions as a % of Carbon storage decreases. This is due to the large amount of N2O emissions released on site during the first year of fertilization.

Fertilization of a near-end-of-rotation coastal Fd stand with 200 kg N/ha had resulted an increase in NEP from 3.3 to 5.3 tonne C/ha/yr, yet, these results also revealed that ~5% of the applied N was lost in the form of highly potent N_2O in the first year after fertilization (Jassal et al., 2008b). Thus, after accounting for NO2 and CO2 emissions from manufacturing, transport and application, the Greenhouse Gas global warming potential resulted in a decreased net change over the first year (Jassal et al., 2008b).

Analysis of the second year produced a similar increase in NEP as in the first year after fertilization; however there were no N2O emissions during the second year (Jassal et al., 2008b). Thus, these results suggest that N fertilization may in fact be viable in increasing C sequestration over the long run, when applied to near-end-of-rotation stands.

A report from the Pacific institute for Climate Solutions shows that recent research shows that net C sequestration in temperate and boreal forests has increased in response to elevated N deposition (Black et al., 2008).

Canary et al. (2000) observed that fertilization of 40 year-old Douglas-fir stands in western Washington at 1000 kg N/ha over 16 years resulted in an increase in C sequestration averaging 1 tonne C /ha/yr over 24 years (Black et al., 2008). N fertilization of these coastal Douglas-fir stands at a cost of $300/ha (including fertilizer and its aerial application) resulted in an additional sequestration of 7.3 Mg CO_2 ha$_{-1}$ y$_{-1}$ (~7.5 m$_3$ wood /ha/yr) in the first two years (Jassal et al., 2008d).

A carbon balance study of containerized *Larix gmelinii* seedlings in the Russian Far East from 1998-2000 determined that carbon levels emitted to the atmosphere resulting from the inputs required in the seedling growing process exceeded the seedling's sequestration rate by a ratio of 1:40 (Schlosser et al., 2002). The Assessment used mass spectrometry to determine the amount of carbon being sequestered by carbon growth, and determined that over a one year production cycle, the carbon content of the seedlings was ~0.516g per seedling, while the emissions averaged the equivalent of 20.8g of carbon per seedling. This results in a net deficit of 20.28g of carbon per seedling. The study determined the seedling would be in carbon deficit until they were an estimated 74.68cm tall (Schlosser et al., 2002).

Discussion

The following table is the source of the ministry standard response relationships for fertilizing of Coastal Douglas-fir (TIPSY 2007). The numbers, which represent the calculated fertilizer response used by Tipsy v. 4.1c, were originally generated by TASS, representing stands planted with 1200 trees/ha.

A range of site index potentials and varying application ages for the stands are included (Tipsy 4.1 2007). However, there is no clear account to how much or what type of fertilizer is used. Nonetheless, the results still clearly show the potential for accelerated stand development with the application of fertilizers.

The gain over 10 years is calculated as (From Tipsy 2007):

- Total volume gain (m3/ha) = fertilized growth – untreated growth
- Total volume gain (%) = 100 x fertilized growth/untreated growth

Coastal Douglas-fir

Site index (m)	Application Height(m)	Age(yrs since planting)	Gain in total volume (m3/ha)	(%)
10	5	22	3	21
10	10	56	4	31
10	15	137	3	50
15	*5*	*16*	*6*	*19*
15	*10*	*32*	*13*	*33*
15	*20*	*96*	*9*	*53*
15	*25*	*182*	*4*	*44*
20	5	13	11	21
20	10	29	23	36
20	20	55	25	56

20	25	82	18	53
20	30	129	11	46
25	5	12	18	23
25	10	20	35	33
25	20	40	40	50
25	30	74	25	43
30	5	10	18	17
30	10	17	32	23
30	20	32	39	32
30	30	54	30	29
30	40	90	19	30
35	5	9	2	1
35	10	15	4	2
35	20	27	4	2
35	30	43	3	2
35	40	66	3	3
35	45	83	2	3

Ministry Recommended Fertilization Response (from TIPSY 4.1 2007 incl. Ministry Standard Database, 2006)

The following table represents the ministry standard response for fertilizer treatment of Coastal Douglas-fir with a site index of 25m:

Site index (m)	Application Height(m)	Age(yrs since planting)	Gain in total volume (m3/ha)	(%)
25	5	12	18	23
25	10	20	35	33
25	20	40	40	50
25	30	74	25	43
Average	*16.25*	*36.5*	*29.5*	*37.25*

Table 12: ministry standard response for fertilizer treatment of coastal Fd with a SI 25.

As we can see there is a significant increase in the amount of growth over the unfertilized stands. Figure 3 below shows the relationship between the age of the stand being fertilized, and the response in volume.
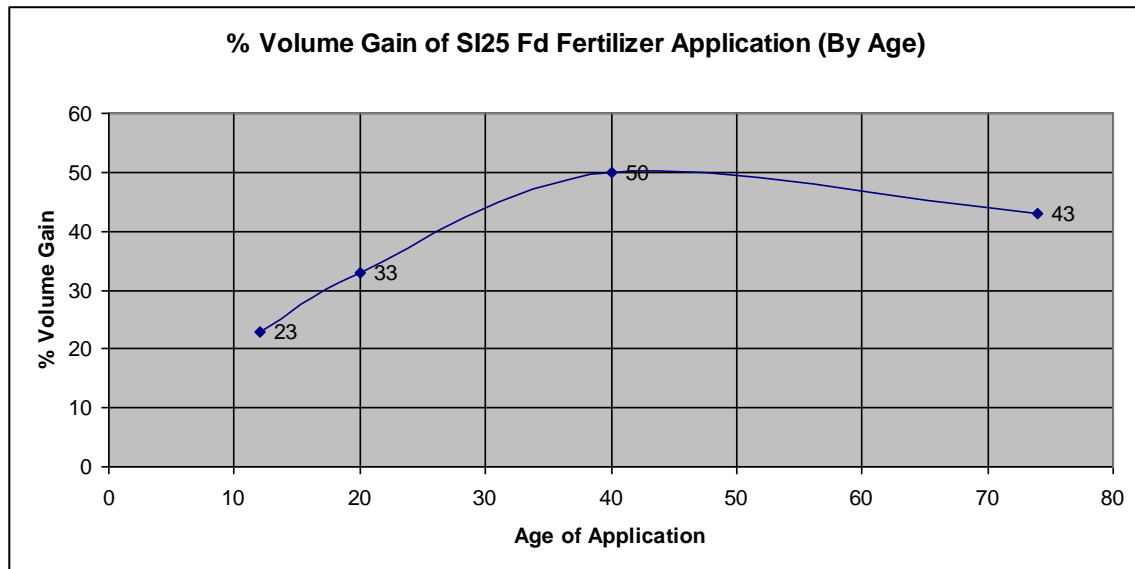
Figure 3: Application age vs. % volume increase for fertilized coastal Fd stands

After approximately 40 years, there is a decrease in the effectiveness of fertilization, although the overall response still yields additional growth. This is likely due to increased mortality and crown cover, as a response to advanced stand development (Ministry Standard Database, 2006).

This can be seen in figure 4 representing the m3/ha response of fertilization to the SI25 Fd:
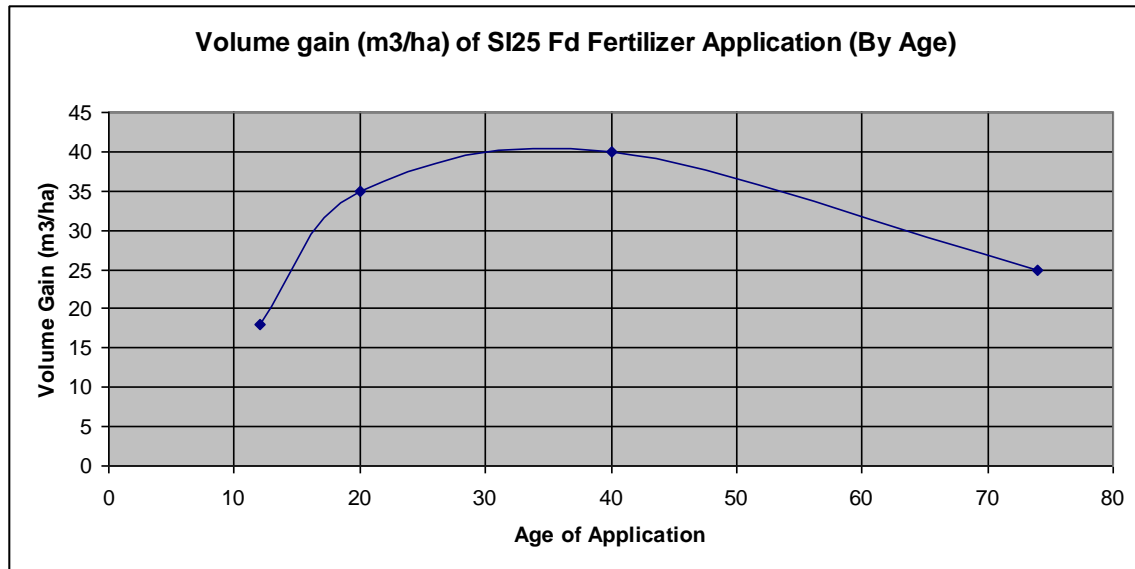
Figure 4: Application age vs. volume gain (m3/ha) for fertilized coastal Fd stands.

Additionally, the ministry recommends that for aerial fertilization, and reduction of 20% is recommended. The ministry used hand fertilization in their study to ensure 100% coverage (Ministry Standard Database, 2006).

Thus,

Example (Ministry Standard Database, 2006)

Species and Density:	Coastal Fd, 1600 trees/ha
Planting Site:	SI 25
Application age:	40yrs
Ministry default response (from table 12):	50% gain
Effectiveness (from aerial distribution):	80%
Net Response (.50 * .80):	**40%**

*The response of the 40 year old coastal Douglas-fir stands can be seen in figures 5 and 6 in Appendix 3.

Or, if we are to use the average numbers derived from table 12:

Species and Density:	Coastal Fd, 1600 trees/ha
Planting Site:	SI 25
Application age:	36.5 yrs
Ministry default response (from table 12):	37.25% gain
Effectiveness (from aerial distribution):	80%
Net Response (.3725 * .80):	**29.8%**

For this example, we can assume a fertilized response in volume gain of 30%.

Tipsy's sourced yield table derived from TASS v2.05.24b 97-oct-09 (using site curves from *Bruce (1981) represent an average stand volume from 247m3/ha for natural stands, to 383m3/ha in planted stands of Coastal Douglas-fir.

If we are to apply the average net response of 29.8% over 10 years we get the following:

Stand Volume (m3/ha)				
Stand Type	**Volume**	**Response Factor**	**Fertilized Volume**	**Gain**
Natural	247	1.298	320.61	*73.61*
Planted	383	1.298	497.13	*114.13*

Thus, we can estimate that for a 1 decade fertilization response, we receive a gain of 114m3/ha in our stand.

The following is a shorthanded estimation of tree volume to CO_2e from the Feasibility Assessment of Afforestation for Carbon Sequestration (FAACS) Appendix B:

Tree Part	Volume (m3)	Conversion factors for tonnes CO2e	Metric Tonnes CO2e	Kg of CO2e (per 1m3)
Main Stem (merchantable)	1.000 m3	1.0m3 x .37 x .5 x 3.667	.678 tonnes	*678*
Non-merch top	.454 m3	1.0m3 x .454 x .37	.308 tonnes	*454*

		x .5 x .3667		
Below Ground Root Mass	.396 m3	1.0m3 x .396 x .37 x .5 x .3667	.0269 tonnes	*396*
Total	1.850 m3	1.850m3 x .37 x .5 x .3667	1.255 tonnes	*1850*

Applied to our fertilized stand volume gain we get:

CO2e Gain (Kg of CO2e)			
Stand Type	**Gain (m3/ha)**	**Conversion Factor to CO2e**	**Total CO2e storage gained / ha**
Natural	73.61	1850	*136178.5kg CO2e*
Planted	114.13	1850	*211140.5kg CO2e*

Sonne (2006) determined that roughly 1.9Mg CO2e /ha /yr was emitted due to fertilizing a stands rotation. However, 30% of this was indirect costs from production and transport (Sonne 2006):

1900kg CO2e * .30 = 570kg CO2e /ha /yr from production
1900 kg CO2e *.70 = 1330kg CO2e /ha /yr from application.

Over 10 years, these numbers become:

Emissions from production	5700 kg CO2e /ha
Emissions from application	13300 kg CO2e /ha
Total Emissions	**19000 kg CO2e /ha**

Thus, our emissions from the production, transport and application of fertilizers to the stands account for 9% - 14% of the on site storage of a 36 year old stand of Coastal Douglas-fir with a site index of 25.

While these results may appear somewhat higher than Sonne's in table 11, the numbers make reasonable sense: the fertilization in this example is occurring at ~ 35 years, and only takes into account the initial decade after fertilizing. The figures more reasonably represent the results from a 10 year rotation age. As seen from Jassal et al., 2008b, the majority of the application emissions occur in the initial year of application, thus these emissions would realistically be spread out over the previous few decades.

Conclusion

The Ministry of Forests and Range guidebook to fertilization suggests that a forest stands' response to fertilization is best to be considered as a reduction in rotation length, i.e. an acceleration in stand development (MOF 1995). They also suggest that a fertilized crop will not generally differ significantly from a non-fertilized crop that is grown over a longer period of time (MOF 1995).

This, however, does fulfill the general goal of landowners who intend to use their forests for carbon sequestration practices: it provides an advantage for establishing seedlings, and allows for quicker establishment of the stand and thus quicker on-site storage.

Part of the objections commonly raised against the use of fertilizers at the time of planting is based on biological bases. It is suggested that during this time the critical need for the seedling is for moisture, not nutrients (Maki, 1966). In addition, it may be possible that fertilizing at the time of planting may stimulate vigorous growth of adjacent grass and vegetative competition (Maki 1966).

However, it is clear that in a nutrient deficient environment, the benefits of using fertilizers at the seedling stage can promote the health and vigor of the individuals (Uddin 2009). In addition, fertilization of near-end-of rotation stands can produce significant increased storage at more advance stages of the stand's development (Black et al. 2008, Jassal et al., 2008b).

While the short term emissions and their related impact on carbon sequestration vary with the species, site productivity, and intensity of the practice, the long term benefits of the seedling establishment and reduction in rotation length make fertilization a viable option for landowners undertaking carbon sequestration projects.

Appendix 1: Results from Seedling Response Test to Fertilizers in Bangladesh (Uddin, 2009).

The following controls (C) and treatments (T) were used:

- C20 – Seedlings of unfertilized plants harvested after 20 days
- C40 – Seedlings of unfertilized plants harvested after 40 days
- C60 – Seedlings of unfertilized plants harvested after 60 days
- C80 – Seedlings of unfertilized plants harvested after 80 days
- T20 – Seedlings of fertilized plants harvested after 20 days
- T40 – Seedlings of fertilized plants harvested after 40 days
- T60 – Seedlings of fertilized plants harvested after 60 days
- T80 – Seedlings of fertilized plants harvested after 80 days

Table 1. Shoot length, root length, collar diameter and root diameter of *A. chinensis, A. saman* and *P. pinnata* at different harvest intervals (days) in control and treatments (fertilized soil) under nursery conditions

| Species | Shoot length (cm) | | | | | | | |
| | Harvesting at 20th day | | Harvesting at 40th day | | Harvesting at 60th day | | Harvesting at 80th day | |
	C_{20}	T_{20}	C_{40}	T_{40}	C_{60}	T_{60}	C_{80}	T_{80}
A. chinensis	27.00b	25.67b	47.00a	33.00b	45.33a	55.33a	37.50ab	59.33a
A. saman	34.33a	34.83c	48.67a	45.67bc	53.33a	59.00ab	52.67a	66.33a
P. pinnata	43.67bc	37.67a	50.00ab	39.33a	60.33a	44.33a	65.33a	45.00a
Species	Root length (cm)							
	Harvesting at 20th day		Harvesting at 40th day		Harvesting at 60th day		Harvesting at 80th day	
	C_{20}	T_{20}	C_{40}	T_{40}	C_{60}	T_{60}	C_{80}	T_{80}
A. chinensis	18.33a	13.83a	22.33a	19.00a	24.33a	23.67a	27.67a	25.00a
A. saman	19.33a	14.50b	20.67a	17.33b	36.00a	40.33a	26.67a	27.67ab
P. pinnata	35.6a	19.00b	30.33a	41.33a	31.33a	40.67a	28.33a	45.67a
Species	Collar diameter (mm)							
	Harvesting at 20th day		Harvesting at 40th day		Harvesting at 60th day		Harvesting at 80th day	
	C_{20}	T_{20}	C_{40}	T_{40}	C_{60}	T_{60}	C_{80}	T_{80}
A. chinensis	2.52b	2.50b	4.75a	3.45b	4.48a	4.90a	3.60ab	6.08a
A. saman	4.60a	4.53b	5.72a	5.02b	6.12a	7.48a	6.60a	7.92a
P. pinnata	5.93a	6.37a	7.80a	8.05a	7.71ab	7.42a	8.27a	7.53a
Species	Root diameter (cm)							
	Harvesting at 20th day		Harvesting at 40th day		Harvesting at 60th day		Harvesting at 80th day	
	C_{20}	T_{20}	C_{40}	T_{40}	C_{60}	T_{60}	C_{80}	T_{80}
A. chinensis	4.17a	5.67ab	5.67a	5.83ab	4.33a	4.50b	5.00a	6.67a
A. saman	6.00a	6.83a	5.67a	5.50a	5.67a	6.50a	6.00a	5.50a
P. pinnata	5.83a	6.50b	7.50a	8.33a	7.00a	5.50b	5.83a	5.50b

Notes: *Values in the columns followed by the same letter (s) are not significantly different (p<0.05) according to Duncan's Multiple Range Test (DMRT)

Table 2. Number of leaves, nodule number and nodule size (mm) of *A. chinensis*, *A. saman* and *P. pinnata* at different harvest intervals (days) in control and treatments (fertilized soil) under nursery conditions

Species	Number of leaves							
	Harvesting at 20th day		Harvesting at 40th day		Harvesting at 60th day		Harvesting at 80th day	
	C_{20}	T_{20}	C_{40}	T_{40}	C_{60}	T_{60}	C_{80}	T_{80}
A. chinensis	8.00a	9.33b	11.33a	10.30ab	10.00a	12.3a	10.60a	11.0ab
A. saman	11.60a	8.67c	11.00a	10.00bc	12.00a	14.0ab	12.60a	15.30a
P. pinnata	10.30a	11.00a	14.00a	18.00a	10.00a	15.30a	11.60a	13.00a

Species	Nodule number							
	Harvesting at 20th day		Harvesting at 40th day		Harvesting at 60th day		Harvesting at 80th day	
	C_{20}	T_{20}	C_{40}	T_{40}	C_{60}	T_{60}	C_{80}	T_{80}
A. chinensis	26.67ab	27.00a	33.00a	26.00a	13.33b	28.33a	11.67b	28.33a
A. saman	39.33a	27.33b	34.33a	29.33b	36.67a	43.33b	31.67a	63.33a
P. pinnata	16.33a	23.67a	15.33a	4.33b	1.00b	1.00b	6.67ab	0.00b

Species	Nodule size (mm)							
	Harvesting at 20th day		Harvesting at 40th day		Harvesting at 60th day		Harvesting at 80th day	
	C_{20}	T_{20}	C_{40}	T_{40}	C_{60}	T_{60}	C_{80}	T_{80}
A. chinensis	1.47b	2.02a	3.08a	1.90a	1.72b	2.75a	1.77b	3.47a
A. saman	1.92b	4.53ab	4.67a	4.90a	2.95ab	2.10b	3.22ab	3.73ab
P. pinnata	2.47a	3.05a	3.10a	2.57b	1.72a	1.60c	3.00a	0.00d

Notes: [*]Values in the columns followed by the same letter (s) are not significantly different (p<0.05) according to Duncan's Multiple Range Test (DMRT)

Appendix 2: Fertilizer Production Emissions Results (Wood and Cowie 2004)

Product	Country	Composition	g CO2e	
		N:P:K	Per kg N	Per kg Product
Ammonia	Norway	82:0:0	1829	1500
Ammonia	Netherlands	82:0:0	2637	2163
Ammonia	Europe	82:0:0	2087	1711
Ammonia	Europe Average	82:0:0	2329	1910
Ammonia	Europe Modern Tech	82:0:0	2024	1660
Ammonia	West Europe	82:0:0	1402-1585	1150-1300
Ammonia	Canada	82:0:0	1951	1600
Ammonia	USA (ammonia plant)	82:0:0	1536	1260
Ammonia	USA	82:0:0	1491	1223
Ammonia	Australia	82:0:0	1524-2195	1250-1800
From Wood and Cowie 2004				

Table 3: Greenhouse Gas Emissions factors for Ammonia Production (from Wood and Cowie 2004)

Product	Country	Composition	g CO2e	
		N:P:K	Per kg N	Per kg Product
Nitric Acid	USA	22.2:0:0	2818-12681	620-2790
Nitric Acid	Norway	22.2:0:0	2818	<620
Nitric Acid	Norway	22.2:0:0	5636-7045	1240-1550
Nitric Acid	Norway	22.2:0:0	8454-10568	1860-2325
Nitric Acid	Japan	22.2:0:0	3100	682-1767
Nitric Acid	Canada	22.2:0:0	11977	2635
Nitric Acid	Canada	22.2:0:0	28188	<620
Nitric Acid	USA	22.2:0:0	13384	2945
Nitric Acid	USA	22.2:0:0	2818	620
Nitric Acid	Sweden	22.2:0:0	10244	2253
Nitric Acid	Sweden	22.2:0:0	12710	2796
Nitric Acid	Europe Ave	22.2:0:0	9000	1980
Nitric Acid	Europe (modern)	22.2:0:0	2500	550
Nitric Acid	Netherlands	22.2:0:0	10851	2387
Nitric Acid	Europe	22.2:0:0	9035	1987
From Wood and Cowie 2004				

Table 4: Greenhouse Gas Emissions factors for Nitric Acid Production (from Wood and Cowie 2004)

Product	Country	Composition	g CO2e	
		N:P:K	Per kg N	Per kg Product
AAN	Europe Ave	35:0:0	7030	246
AN	Europe Ave	33.5:0:0	6806	2280
AN	Europe Modern	33.5:0:0	2985	1000
AN	Netherlands	33.5:0:0	7108	2381
AN	UK	33.5:0:0	6536	2189
AN	Europe	33.5:0:0	6726	2253
CAN	Sweden	27.6:0:0	8467	2336
CAN	Sweden	27.6:0:0	9562	2639
CAN	Sweden	27.6:0:0	9562	2601
CAN	Europe Ave	26.5:0:0	7481	1982
CAN	Europe Ave	26.5:0:0	6867	1820
CAN	Europe Modern	26.5:0:0	3018	800
CAN	Netherlands	27.9:0:0	6810	1900
Mean N Fert	Germany	28.6	7615	2178
Mean N Fert	Germany	27.7	5339	1479
Mean N Fert	Germany	27.7	5644	1563
Mean N Fert	USA	-	857	-
From Wood and Cowie 2004				

Table 5: GHG emission factors for AN, CAN, and Mean N Fertilizers (from Wood and Cowie 2004)

Product	Country	Composition	g CO2e	
		N:P:K	Per kg N	Per kg Product
Urea	Europe Ave	46:0:0	4018	1848
Urea	Europe Ave	46:0:0	1326	610
Urea	Europe Modern	46:0:0	913	420
Urea	Europe	46:0:0	1703	785
UAN	Europe	32:0:0	3668	1173
UAN	Europe Ave	32:0:0	5762	1844
UAN	Europe Ave	32:0:0	4093	1310
UAN	Europe Modern	32:0:0	2000	640
From Wood and Cowie 2004				

Table 6: GHG emissions factors for Urea and UAN production (from Wood and Cowie 2004)

Product	Country	Composition	g CO2e	
		N:P:K:S	Per kg N	Per kg P2O5
SSP	Europe Ave	0:21:0:23	-	1051
SSP	Europe Ave	0:21:0:23	-	95
SSP	Europe Modern	0:21:0:23	-	-238
TSP	Europe Ave	0:48:0:0	-	1083

TSP	Europe Ave	0:48:0:0	-	354
TSP	Europe Modern	0:48:0:0	-	-416
MAP	Europe Ave	11:52:0:0	6392	1352
MAP	Europe Ave	11:52:0:0	2818	596
MAP	Europe Modern	11:52:0:0	-2454	-519
DAP	Europe Ave	18:46:0:0	4812	1883
DAP	Europe Ave	18:46:0:0	2555	1000
DAP	Europe Modern	18:46:0:0	-388	-152
Mean P Fert	Germany	0:32.2:0:0	-	817
Mean P Fert	Germany	0:38.5:0:0	-	458
Mean P Fert	Germany	0:35.5:0:0	-	700
P Fertilizer	US	-	-	165
From Wood and Cowie 2004				

Table 7: GHG emission factors for phosphate fertilizers (from Wood and Cowie 2004)

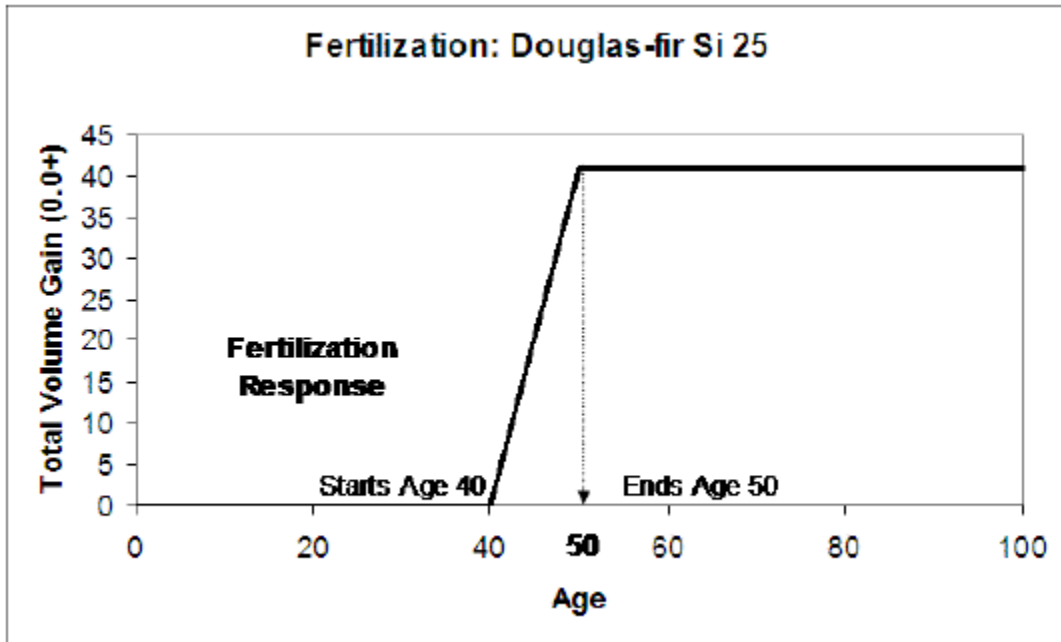## Appendix 3: Ministry response charts for fertilization of 40 year old Coastal Fd with SI 25.

Figure 5: Fertilization response of 40yr old Coastal Fd (Total Volume Gain)
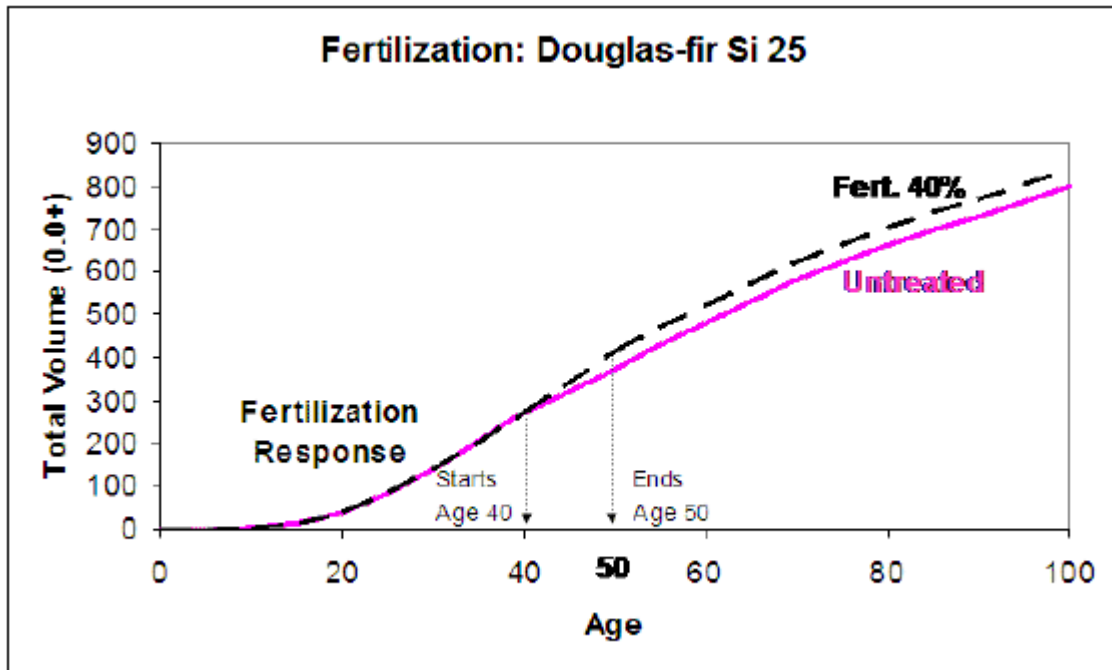

Figure 6: Fertilization response of 40yr old Coastal Fd (Total Volume of stands)

Appendix 4: Building Block Structure and associated energy use of different Fertilizer grades (From Kongshaug 1998)
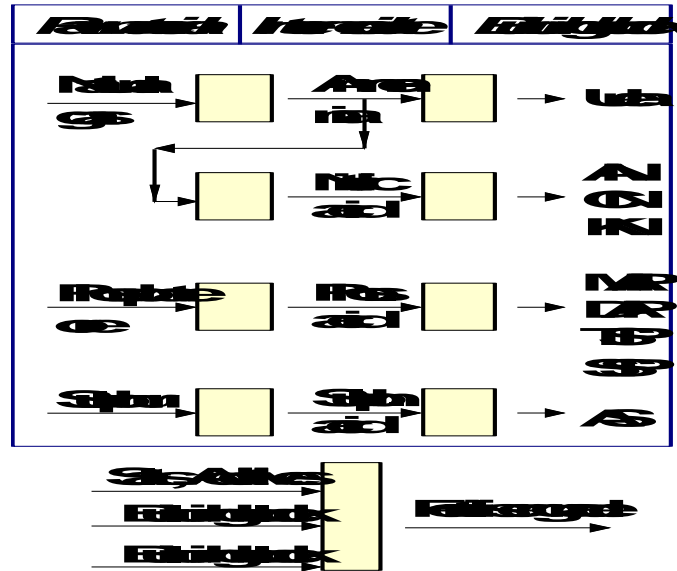

Figure 1: Fertilizers broken into product building blocks (from Kongshaug 1998)

Table 8 - Accumulated Energy Consumption for Building Blocks and Some Fertilizer Grades (From Kongshaug 1998, and Torre 2003)

Product building blocks		"Old" tech. GJ/t	Av. Europe GJ/t	Modern tech. GJ/t	"Old" tech. t CO$_2$/t*	Av. Europe t CO$_2$/t*	Modern tech. t CO$_2$/t*	Feed energy GJ/t	Feed CO$_2$ t CO$_2$/t
NH$_4$	82-0-0	41.0	32.0	28.3	2.51	1.91	1.66	23.37	1.33
AP	11-49-0	9.0	5.0	-3.1	0.57	0.30	-0.24	3.14	0.18
NITRO AP	8.4-52-0	7.5	7.2	5.1	0.48	0.45	0.31	2.57	0.15
Urea	46-0-0	27.6	22.1	19.2	0.98	0.61	0.42	13.11	0.75
AN	35-0-0	19.1	13.5	10.7	2.58	2.38	1.05	10.28	0.59
AS	21-0-0-23	9.8	6.0	2.9	0.60	0.34	0.14	5.99	0.34
CN	15.5-0-0	12.1	6.4	4.9	1.93	1.69	0.65	4.55	0.26
KN	14-0-44	19.1	11.3	9.6	2.36	1.97	0.95	4.24	0.24
MAP	11-52-0	9.2	5.0	-3.5	0.59	0.31	-0.27	3.14	0.18
DAP	18-46-0	12.3	7.7	-0.3	0.77	0.46	-0.07	5.13	0.29
TSP	0-48-0	4.2	2.5	-2.9	0.28	0.17	-0.20	0.00	0.00
SSP	0-21-0-23	1.0	0.3	-0.8	0.07	0.02	-0.05	0.00	0.00
MOP	0-0-60	4.0	3.0	1.5	0.27	0.20	0.10	0.00	0.00
SOP	0-0-50-46	2.0	1.4	-0.7	0.13	0.10	-0.04	0.00	0.00
Liq. UAN	32-0-0	28.8	21.9	18.2	1.53	1.31	0.64	9.12	0.52
Derived products									
CAN	26.5	14.8	10.6	8.4	2.0	1.82	0.80	7.87	0.45

AN	33.5	18.3	13.0	10.2	2.5	2.28	1.00	9.84	0.56
PK	22-22-0	3.5	2.4	-0.7	0.23	0.15	-0.05	0.00	0.00
NPK	15-15-15 Phosph. acid	10.2	6.9	3.1	1.10	0.93	0.30	4.37	0.25
NPK	15-15-15 Nitrophosphate	8.5	6.7	4.9	0.87	0.80	0.40	3.45	0.20
NPK	15-15-15 AS/TSP/MOP	9.4	6.0	1.2	0.59	0.36	0.04	4.13	0.24
NPK	15-15-15 Urea/TSP/MOP	11.4	8.8	5.8	0.48	0.30	0.10	4.27	0.24
ANS	26-0-0-35 AN+AS	13.2	8.8	5.9	1.3	1.12	0.49	7.53	0.43
UREAS	40-0-0-14 Urea + AS	23.3	18.2	15.3	0.9	0.55	0.35	11.40	0.65
NS	24-0-0-12, AN + gypsum	13.4	9.5	7.6	1.8	1.64	0.72	7.10	0.40

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