Study of woody fibre in papermill sludge

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ABSTRACT

In order to determine the role that papermill sludge plays in the organic carbon cycle of the forest products industry, a global model of sludge generation has been created. Analysis of mixed sludge output of six Ontario papermills derived fundamental data on the characteristics of sludge. A methodology to identify and quantify the woody organic material present in the sludge matrix was developed. The wood chemical composition of the woody organic fraction of each sludge stream was investigated. The results of physical and chemical testing were then compared to validate the proposed methodology. On the basis of this analysis, mill outputs were divided into three categories related to mill parameters.

The physical properties of sludge fibres were found to be linked to the presence or absence of recycled fibres, and showed little correlation to the pulping technique or recovery method employed. The chemistry of the organic fraction of sludge was found to be more closely related to mill process. It is shown that the basic holocellulose and lignin compositions follow a normal distribution for each of the three mill categories. Sludges produced at primary installations, which use primarily virgin fibre, were found to have the largest component of woody organic material. Recycling and deinking operations had a lower proportion of fibre in the sludge stream.

In order to understand global patterns of papermill sludge production, trends in paper and paperboard production, consumption, and recovery were analyzed and projected until the year 2050. Parameters used in describing trends included population parameters (size, density, and literacy rate), as well as fibre supply parameters (forest, plantation, and nonwood fibre supply). The model accounted for 80% of paper consumption, 94% of paper production, and 96% of paper recycling at high correlation coefficients.

A major shift in the global pattern of sludge production is predicted, with Asia emerging as the second largest sludge-producing region. Global production of papermill sludge will rise to 4,800,000 metric tons in 2050. The fraction of sludge material deriving from wood fibres will decline, reducing potential for fibre recovery and lowering the possible contribution of sludge towards carbon sequestering.

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1 Introduction

1.1 Historical background

1.1.1 Environmental considerations

Since the 1960's, the environmental movement has become prominent in most of the industrialized nations of the world. One issue of great concern is the perceived destruction of the world's forests, through unsustainable harvesting practices and unimpeded expansion of agricultural and urban landscapes. The forest industry has received significant attention in the media regarding the long-term sustainability of its operations. As a result, the industry has initiated an ongoing global assessment of its operations, ideals, and goals. A significant part of this assessment has been to place all aspects of forestry under scientific scrutiny.

A key issue driving research about the environment is the topic of climate change. Most scientists agree that gaseous emissions from the combustion of fossil fuels are the leading cause of climate change, but the reduction in forest area that has been experienced over the last 30 years has likely contributed to the phenomenon (FAO 1999a). In order to offset these emissions, many scientists are looking to the world's forests as potential sinks for atmospheric carbon.

At the Kyoto conference in 1997, the industrial world agreed to stabilize the atmospheric carbon dioxide concentration at approximately 550 ppm, which is double that of pre-industrial ambient atmosphere, and much higher than our current levels of 360-370 ppm (Herzog et al. 2000, O'Driscoll 2000). The target dates for achieving this goal range from 2008-2012, which provide a 15-year window of opportunity for changes to be made (Canadian Forest Service 2000).

The carbon found in forest products accounts for a considerable proportion of the annual forest carbon cycle. Most estimates place the proportion of carbon that is transformed annually into products as between ¼ and ½ of the total carbon sequestered annually by the world's forests (Kellomäki and Karjalainen 1996, Nabuurs 1996). According to some studies, this figure may be as high as 72% (Houghton et al. 1999). The literature does not explicitly describe the ultimate disposition of forest-related carbon in products and emissions, and neglects to address the impact of wood fibre recycling on this cycle. This information will be of considerable interest to the pulp and paper industry as issues related to the carbon cycle continue to grow in importance.

1.1.2 Pulping and recycling

Papermill sludge, hereafter referred to as sludge, is produced as the by-product of the pulp and paper industry. The characteristics of sludge are variable and directly related to the technology used to pulp the wood, and to the type of effluent treatment that is employed.

Mechanical pulping uses physical forces to separate wood fibres, resulting in a high yield pulp that is characterized by shorter fibres and relatively lower strength. Purely mechanical pulps include stone groundwood (SGW) and refiner mechanical pulps (RMP). With some additional heat and/or chemicals, thermomechanical pulps (TMP), chemi-thermomechanical pulps (CTMP) and bleached chemi-thermomechanical pulps (BCTMP) can be produced using refiner technology. Mechanical and semi-mechanical pulps only make up approximately 15% of the total pulp output of North America (Smook 1994). The current trend in the industry has been towards more use of TMP, CTMP, and BCTMP, with correspondingly less investment in groundwood operations.

Chemical pulping techniques use alkaline or acidic chemicals to dissolve lignin, releasing individual fibres. The most popular chemical pulping methodology is the Kraft or sulphate process, which is noted for the efficiency in which pulping chemicals can be recovered and reused. The Kraft process is currently used in approximately 80% of pulp production, and produces strong pulps at a good yield. Sulphite pulping is less efficient in terms of chemical recovery, and is now generally found in older installations. Dissolving pulps and other specialty processes make up the remaining fraction of chemical pulping processes (Smook 1994). The industry is moving towards almost exclusive utilization of the Kraft process.

One side effect of increasing environmental awareness is the increase in wastepaper recycling. Since the late 1970's, wastepaper recovery has risen steadily, and is approaching 40% of paper consumed in much of Europe and North America (Holbery et al. 2000). Recycling has created a new range of problems that must be addressed. In order to create newsprint or fine paper products, recovered paper must be deinked, a process that creates additional wastewater and solid waste by-products. Flotation deinking cells are today used in the processing of approximately 20% of the wastepaper supply (Biermann 1996). A large proportion of the paper being recycled is processed in or near major urban centers, which means that the disposal of solid waste must be handled differently than in more remote locations.

1.1.3 Papermill sludge

Sludge is a viscous, wet material when it is first collected. It can contain woody fibres, dirt, ink, stickies (agglomerated material containing resins, plastics, or glues introduced through the pulping or recycling process), flocs (large bundles of fibres removed from the forming line), organic material including bacteria used in the secondary treatment of waste water, and other miscellaneous materials, including glass and metal to a small degree. The principal component of sludge is water, which makes up more than half of the total mass of sludge even after dewatering.

Sludge is produced at both pulp and paper mills. Many mills are integrated; that is to say, they pulp fibre from raw materials, and then turn that fibre into paper. Recycled paper mills can be considered integrated as well, and include additional stages to clean inks and other foreign material from the wastepaper stream. This study refers to paper mills for the most part, but mills devoted only to pulping are included in the model as well.

Typically, the characteristics of sludge are measured in terms familiar to waste stream experts; biological oxygen demand, chemical oxygen demand (COD), absorbable organic halides (AOX), and suspended solids (SS). The current trend towards recycling has increased the amounts of sludge produced significantly. In the United States, for instance, the total amount of sludge produced has been estimated to have doubled over a 20 year period (Amberg 1988).

Primary sludge

Primary sludge is produced through the physical cleaning of the wastewater stream, and is collected in screens and filters. It is fairly easy to dewater due to the high proportion of woody organic material within the sludge, and the relatively high fibre-fines ratio of the organics. This stream is often combined with secondary sludge for disposal.

When primary sludge is produced in a virgin fibre pulp or paper mill, the material is fairly clean, consisting of wood fibres, fines, some inorganic fillers, and water. A repulping operation produces a slightly higher amount of primary sludge containing a much higher fraction of contaminants, including plastics, clays, and other chemicals. In a deinking operation, generation rates are typically in the range of 5 times that of virgin fibre mills (Bellamy 1995, Bruce 1994, Badar and Cutbirth 1993).

Secondary sludge

Secondary sludge is produced through the biological treatment of the wastewater stream. It is composed mainly of bacteria, organic woody material, and ash. Secondary sludge is often associated with odor problems, due to the large fraction of decomposing organic matter within the material. It is difficult to dewater this material, due to the highly colloidal nature of the small particles in suspension. In order to improve dewatering potential, secondary sludge is normally mixed with primary sludge prior to disposal (Bellamy 1995).

1.2 Statement of the question

The generation of papermill sludge poses a global problem that will continue to grow as industrialization continues. Trends in papermaking, recycling, and consumer demand are changing the characteristics of sludge, while an increasing awareness of the environment is making it more difficult to dispose of this material.

In order to truly understand the scope of this problem, it is necessary to consider the world as a whole. Economic costs of disposal vary between countries, but it is postulated that the environmental cost remains the same. Thus, the study will address the issues of papermaking and recycling in terms of total sludge generation, the amount of woody organic material generated within the sludge matrix, and the amount of woody organic carbon contained within the sludge matrix.

The overall goal of the research is to describe the role that sludge plays in the carbon budget of the pulp and paper industry.

1.3 Thesis development

1.3.1 Thesis organization

In order to answer the research question, the thesis is laid out in the following way. Chapter 2 provides an extensive review of the available literature on wood chemistry, sludge, CO_2 cycling, and modeling approaches. Chapter 3 describes the analysis of sludge for woody chemical components, and provides an overview of the physical characteristics of the sludge from a variety of sites. Chapter 4 establishes the relationships between mill type and sludge output, and examines the variability of sludge compositions. Chapter 5 describes the construction of a model of pulp and paper production, consumption, and recycling, based on a variety of physical and social factors. Chapter 6 extrapolates the model ahead to the year 2050, and examines a variety of implications that sludge producers should consider.

1.3.2 Related publications

Portions of the model of paper production, consumption, and recycling were published as part of the Global Fibre Supply Model (Bull et al. 1998a). An early version of the model was published separately in Unasylva (Mabee 1998), and was included in a background report for the Global Fibre Supply Model (Mabee and Pande 1997). The model was developed independently over a period of four years, and has been extensively modified since it's initial publication.

The models for fibre supply variables used in Chapter 5, including curves for forest, plantation, and nonwood fibre supply, were originally created as part of the Global Fibre Supply Model (Bull et al. 1998a). The published values for these variables have not been changed for inclusion in this thesis.

2 Literature Review

2.1 Wood Chemistry

An evaluation of the properties of sludge can follow several paths. Most investigators in the past have focused upon the toxicity of mill effluent, and have ignored the general chemistry of the material within the sludge. This methodology, while suited to judging the effects of mill effluent on the surrounding environment, does little to describe the role that sludge contributes to the life cycle of wood fibres, and the degree to which sludge emissions can affect the carbon cycle of pulp and paper products.

In order to better understand the role that sludge plays, it is necessary to analyze the woody organic component within the sludge. This can be done through physical and chemical analysis of the wood fibres.

Wood is largely composed of three major polymer groups. Two of these groups, commonly described as cellulose and hemicellulose, are closely related and may be jointly referred to as the cellulosics or holocellulose. Cellulose is a generic term that is often used to refer to alphacellulose, which consists of pure chains of β-D-glucose. Hemicellulose refers to what is properly known as beta- and gammacellulose. Hemicellulose degrades into many five- and six-carbon sugars and is characterized by a branched, non-crystalline structure that is difficult to predict. There are also many extraneous substances present in wood, which are often grouped together under the loose heading extractives. Each of these headings describes groups that vary in complexity and diversity (Sjöström 1993, Fessenden and Fessenden 1986, Neish 1959, Nord and Schubert 1959, Paist 1958).

In the wood matrix, the three major structural groups are bound to one another to form a cohesive structure. This makes it virtually impossible to isolate the individual chemical components of wood to 100% purity. Parts of the structure will inevitably be lost in the separation, and the removal of other macro polymers is unlikely to be absolute. Thus, an analysis of wood chemical composition must make allowances for the nature of the wood by taking these facts into account.

The composition of each of the major wood chemical groups, including the major subdivisions and a list of the individual components that go into component synthesis, is shown in Table 2.1.

Table 2.1 Basic components of wood

Group	Major Components	Basic Structural Groups
Alphacellulose	Cellobiose	D-glucose
Hemicelluloses	(i) Pentoses	D-Xylose, L-Arabinose
	(ii) Hexoses	D-Glucose, D-Mannose, D-Galactose
	(iii) Acids	Uronic Acids, Methoxy Uronic Acids, Acetic Acid
Lignin	Phenylpropane Groups	Coumaryl, Guaiacyl, & Syringal Groups
Extractable Substances	(i) Soluble in neutral solvents	Resins, Fatty Acids, Phenolic Substances, Alcohols
	(ii) Insoluble in neutral solvents	Minerals, Proteinaceous matter, Pectic substances

2.1.1 Alphacellulose

Of the three major wood chemical groups, cellulose is the simplest in structure and the easiest to manipulate for industrial purposes. It is also very plentiful, accounting for approximately 50% of the total bound carbon on the planet. An average sample of wood contains in the range of 50% cellulose by mass (Fessenden and Fessenden 1986). The greatest concentrations of alphacellulose are located in the secondary cell wall of wood fibres, where it serves to give wood its rigid structure (Sjöström 1993).

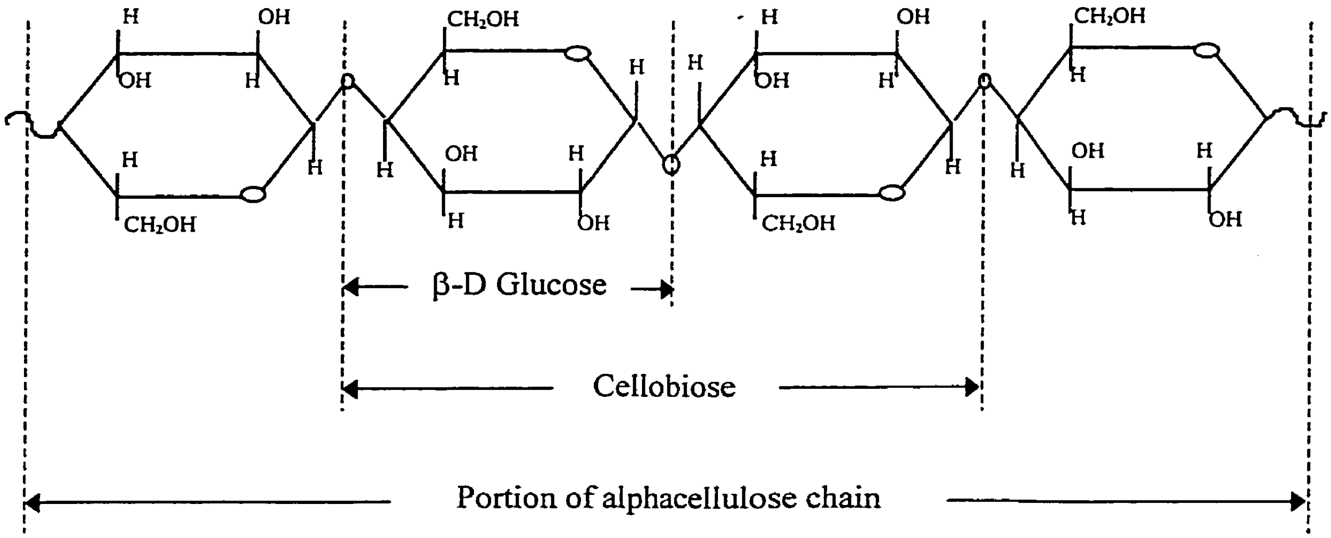


Figure 2.1 Basic structure of alphacellulose

The basic structure of cellulose, as shown in Figure 2.1, takes the form of a long, narrow chain, in which D-glucose units are joined in a 1,4 β-linkage. A combination of two glucose molecules results in the formation of a disaccharide unit referred to as cellobiose. When thousands of cellobiose units are joined end to end, a strand of alphacellulose is created. A typical alphacellulose molecule has a degree of polymerization (DP_n) of approximately 14,000 glucose units.

The absolute chemical formula of alphacellulose is thus $H(C_6H_{10}O_5)_xOH$. Using this formula, it can be deduced that the carbon content of alphacellulose is approximately 44% of the total mass.

2.1.2 Hemicellulose

Hemicellulose is a much more complicated compound than the simple chain of alphacellulose. Table 2.1 lists many of the monomers and acids present in the macromolecule. The variety of compounds provides a number of available bond sites that extend in a non-linear fashion to create the typical branched structure of hemicellulose. This compound has no single defined structure, as the position of various components cannot be foreseen. As a result, hemicellulose responds unpredictably to industrial practices of wood chemical engineering. It can easily be concluded that it is more difficult to work with hemicelluloses, and can have a large effect upon the suitability of fibres for the papermaking process.

Structurally speaking, hemicellulose is a smaller polymer than alphacellulose. It normally displays a DP_n of between 100 and 200 carbohydrate units.

Table 2.2 Mean Hemicellulose elemental composition

	C	H	O	Ratio	Mean % of Structure
Softwoods					
Galactoglucomannan					
β-D-Galactose	6	12	5	1	24%
β-D-Glucose	6	12	5	1	
β-D-Mannose	6	12	5	3	
Acetyl group	2	3	1	1	
Galacto(Glucomannan)					
β-D-Galactose	6	12	5	0.1	45%
β-D-Glucose	6	12	5	1	
β-D-Mannose	6	12	5	4	
Acetyl group	2	3	1	1	
Arabinoglucuronoxylan					
α-L-Arabinose	5	9	4	1.3	31%
4-O-Methylglucuronic acid	7	12	6	2	
β-D-Xylose	5	10	4	10	
Mean Softwood Hemicellulose:	44	86	36		
Hardwoods					
Arabinogalactan					
α-L-Arabinose	5	9	4	0.7	43%
α-D-Arabinose	5	9	4	0.3	
β-D-Galactose	6	12	5	6	
β-D-Glucose	6	12	5	~0.01	
Glucuronoxylan					
4-O-Methylglucuronic acid	7	12	6	1	49%
β-D-Xylose	5	10	4	10	
Acetyl group	2	3	1	7	
Glucomannan					
β-D-Glucose	6	12	5	2	8%
β-D-Mannose	6	12	5	1	
Mean Hardwood Hemicellulose:	39	103	42		
Mean Hemicellulose:	41	95	39		

Source: Sjöström 1993, Pettersen 1984

One must keep in mind that the structure of hemicellulose can vary tremendously, in both size and structure, as the presence of different monomers can change the overall molecule to a large degree. The hemicellulose group typically makes up 20% of the total wood mass.

The monomers present in hemicellulose vary with the type of wood being analyzed. The hemicellulose fraction of hardwoods differs from that of softwoods, and the unique structural properties of each contribute to the differences that hardwoods and softwoods display when subjected to commercial pulping practices. Softwoods respond much better to pulping than hardwoods, due to the simpler morphological and chemical structure that characterizes softwoods.

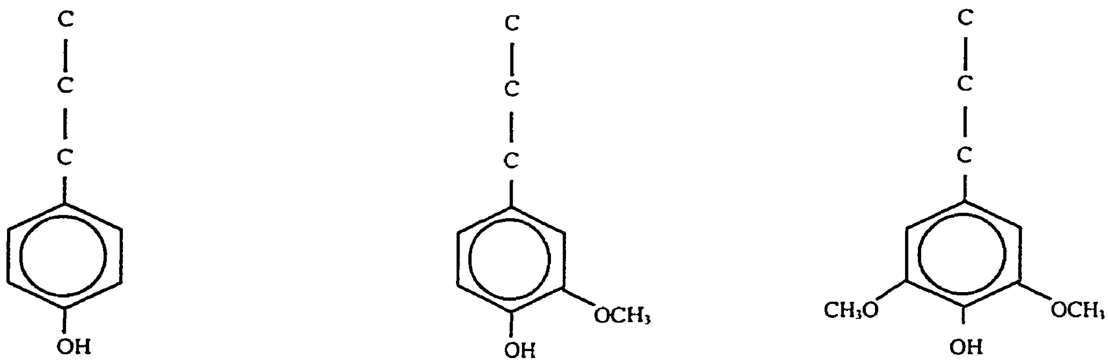
Because the chemistry of hemicellulose is variable, an absolute chemical formula is impossible to determine. However, by examining the average amounts of various components, a mean chemical formula may be ascertained. Table 2.2 compares and averages the carbohydrate content of softwood and hardwood hemicelluloses.

Using the mean chemical formula $C_xH_yO_z$, it can be ascertained that the carbon content for hemicelluloses ranges between 38% (hardwoods) and 44% (softwoods) of the total mass of hemicellulose. Assuming equal inputs, the overall average carbon content for hemicellulose is 41% by mass.

2.1.3 Lignin

Lignin is perhaps the most complicated wood macro polymer. Unlike cellulose and hemicellulose, it is not fibrous in form and is composed principally of aromatic compounds. It is an amalgamation of two (or three) principal phenylpropane groups and their derivatives, which combine in a myriad of ways to produce a very large, amorphous molecule. This molecule appears light brown in colour, but certain chemical procedures such as Kraft pulping can render it nearly black. Lignin acts to bind the various fibrous components of wood together, imparting strength and cohesiveness to the chemical structure. The presence of lignin is considered undesirable by the pulp and paper industry, as it hampers the production of quality paper and imparts colour to the nearly white tone of cellulosic matter.

As stated before, there are three major phenylpropane groups that form the building blocks of lignin. The structures of these groups are presented in Figure 2.2.



Coumaryl Group **Guaiacyl Group** **Syringyl Group**

Figure 2.2 Chemical structure of lignin (Phenylpropane base units)

It is evident from the figure above that these groups are each very similar to each other, being distinguished by the presence or absence of methoxy groups around the phenolic ring. The interesting aspect, in terms of structure, is the wide variety of bond sites that can be invoked during the construction of the macromolecule. The number of sites available leads to the production of many intermediate structures, and this in turn leads to the production of a polymer whose form is impossible to predict. The lignin molecule usually makes up approximately 20% of the total wood mass.

Of the three phenylpropane units, the coumaryl and guaiacyl groups are found in all wood lignins. The syringyl group, however, is found only in the lignin of hardwoods, a fact that alters the chemistry of hardwood lignin significantly. The importance of a change in chemical structure in terms of wood fibre utilization has already been touched upon in the previous section, and the same rational can be applied in this case. The introduction of a third phenylpropane unit allows the lignin of hardwoods to combine in a variety of ways that softwood lignin is incapable of, and it is partially for this reason that hardwoods are more difficult to delignify in the pulping process than are softwoods (Panshin and de Zeeuw 1980).

Because of the difficulties associated with isolating the lignin compound, many features of its structure are currently only theorized. For instance, it is impossible to provide a measurement of DP_n for this molecule. The properties associated with its structure suggest that it is very large in its natural state, but at this point no method exists for a finer evaluation of its size. On a related issue, it should be noted that the determination of lignin content most widely used today has been evolved from Klason's original method, and is essentially an acid dissolution of the pulp that leaves an insoluble residue. This method is less a precise extraction of polymer concentration than a convenient standard, introduced and used by researchers in the pulp and paper industry (Fengel and Wegener 1984).

Table 2.3 Mean elemental composition of Lignin

	C		H		O	
Species	**# of atoms***	**% mass**	**# of atoms***	**% mass**	**# of atoms***	**% mass**
Softwoods						
Spruce	9.96	65%	11.71	6%	3.33	29%
Spruce	9.90	65%	11.40	6%	3.27	29%
Spruce	9.92	65%	10.64	6%	3.42	30%
Spruce	9.98	63%	11.64	6%	3.58	30%
Spruce	9.94	64%	11.02	6%	3.54	30%
Spruce	9.92	62%	11.66	6%	3.77	32%
Spruce	9.95	64%	10.45	6%	3.55	30%
Mean Softwood Lignin:	9.9	64%	11.2	6%	3.5	30%
Hardwoods						
Birch	10.58	60%	13.77	7%	4.35	33%
Beech	10.52	61%	12.02	6%	4.24	33%
Mean Hardwood Lignin:	10.6	61%	12.9	6%	4.3	33%
Mean Lignin:	10	61%	12	6%	4	33%

*All figures denote average number of atoms in the chemical structure

Source: Sarkanen 1963

From the data shown in Table 2.3, it can be seen that the carbon content of lignin ranges from 61% (softwoods) to 63% (hardwoods) by mass, with an average of 62% carbon by mass of lignin.

2.1.4 Extractives and Trace Elements

These two components of wood are similar in that they exist in the wood, but are not intrinsic parts of the wood matrix itself. The presence of both groups is explained by the fact that trees are living organisms, and exist as components in an ecosystem. Extractable chemicals found within the wood are associated with the living tree, and serve no structural function in the way that fibres or tracheids do. The extractive group normally forms the smallest portion of the total wood mass, but contains many interesting compounds that are becoming more important in the modern world quest for pharmaceutical and chemical goods. Some of these substances include acids, tannins, sugars, resin, resenes, turpenes, gums, and waxes. In total, extractive substances compose only 1-5% of the total wood mass. The carbon content of this material is difficult to estimate due to the variable nature of the components.

2.2 Production of Sludge

2.2.1 Types of sludge

As stated in the first chapter, sludge can be separated into two major categories, primary and secondary sludge. Primary sludge is a fibre-rich material formed from mechanical cleaning of the wastewater stream. Secondary sludge is material produced through activated wastewater treatments and composed of a combination of organic and inorganic detritus that includes fibres, fines, bacterial cells, and other waste.

In some installations, the effluent from various stages of the pulping or papermaking process is treated separately. The resulting sludges are then combined for disposal. Other mills prefer to combine the effluent streams from all stages of production. In this approach, the total mill effluent (TME) is subjected to a single primary and secondary treatment. This approach is highly adaptable to fundamental changes in the types of effluent produced (Lo et al. 1994b).

Primary sludge

Primary sludge consists primarily of woody fibres and fines, and as such is the easiest material to characterize and reuse. In a virgin pulp mill, this material is fairly 'clean', consisting only of woody waste material and dirt washed out of the raw material. In a recycling plant, the primary sludge will also include synthetic materials such as plastics and stickies, as well as traces of glass or metal.

After complete processing, primary sludge can vary in moisture content from 30 to 70%, depending on the technology used to dry the materials and the targeted final moisture content (Coburn and Dolan 1995). Primary treatments are effective at removing suspended solids, but do not reduce BOD (biological oxygen demand) levels to any great extent (O'Connor et al. 2000). Primary treatments have been shown to be effective in reducing the amount of heavy metals present in wastewater (NCASI 1991).

Deink sludge

Deink sludge is by definition a primary sludge that is produced through the mechanical treatment of deinking effluent. In many installations, it is considered part of the total primary sludge, as it is produced through the same mechanical cleaners and filters as other primary sludges. However, it is much dirtier and more difficult to deal with than other primary sludge, and for this reason is often kept separate.

The most common methods used to deink paper products are flotation deinking and mechanical cleaning. Most often, these approaches are taken together in order to ensure that a majority of particles at any range of size are being removed. Flotation deinking is widely used in North America, Europe, and Asia. Chemicals added during flotation deinking of pulps include flocculants that make the ink particles coagulate, and surfactants that affect and enhance the hydrophobic nature of ink within the water suspension. Caustic (NaOH) is also often added, in order to increase the pH and to assist in densification (Ferguson 1992).

The process of flotation deinking can result in the removal of a large number of fibres from the pulp stream. Without recovery, these fibres can ultimately become part of the primary or deink sludge stream. This problem seems to be exacerbated by the use of old newsprint (ONP) (Deng 2000). It has been shown that washing the froth associated with flotation deinking can result in significant fibre recovery (Robertson et al. 1998).

Secondary sludge

Secondary sludge is produced through activated wastewater treatments in a similar fashion to the treatment of municipal sewage. This treatment can utilize aerobic and/or anaerobic bacteria.

One way in which aerobic treatment of effluent can be achieved is through the use of an aerated stabilization basin (ASB) or lagoon. An aerated stabilization basin uses a large basin or lagoon where the bio-organisms are activated with the addition of air, and the solids are precipitated out directly into the basin. The solid sludge can then be removed through dredging or draining of the settling basin. The presence of excess air and food substrate in the system allows for the rapid development of aerobic bacteria, which then breaks down the material carried within the waste stream. While the ASB process is effective at reducing much of the toxicity of the effluent, certain chemicals, such as pentachlorophenol, have been shown to remain at chronically toxic levels (Cowan et al. 1995). Secondary effluent treatment has been found effective in biodegrading certain compounds, such as ethylenediaminetetraacetic acid (EDTA), which currently have poorly understood effects on the environment. Under alkaline conditions (pH > 8), an ASB system was found to reduce EDTA by up to 50% (Virtapohja and Alén 1998).

A second option for aerobic treatment of sludge is an activated sludge (AS) system, which uses tanks holding highly aerated wastewater. The solid precipitate is held in suspension and removed in a sedimentation tank known as a secondary clarifier. The benefit of an AS system is that it requires less time and area to implement; however, more hardware is necessary and the microbial concentrations are much higher and harder to maintain in balance (Johnson and Chatterjee 1995).

ASB and AS treatments are both equally effective at lowering BOD of the effluent stream, with reductions of greater than 90% being common. The effectiveness of these treatments is reduced slightly when treating the effluent from a deinking operation (NCASI 1991).

More refined versions of secondary effluent treatment usually include an anaerobic or hybrid aerobic-anaerobic pretreatment, which cultivates the presence of different bacteria under oxygen starvation in order to improve upon the percentage of removal (Cowan et al. 1995). The use of an anaerobic system without a corresponding aerobic system, however, will not detoxify the sludge (Lo et al. 1994a). Anaerobic treatment systems are responsible for producing many of the compounds that contribute to manure-like odors that have come to be associated with secondary sludge (O'Connor et al. 2000).

Certain chemicals can be used to precipitate secondary sludge from a suspended solution, including alum ($Al_2(SO_4)_3$) and polyacrylamide polymers. In zero-effluent mills, where it is important to precipitate all materials, these chemicals can be used on a large scale, with up to four tons per day of alum and 0.5 tons per day of polyacrylamide polymers used per day. The solids content of secondary treatment outputs are generally between 0.5 and 3% (Kenny et al. 1995). Even after pressing, the moisture content of secondary sludge tends to be very high. For this reason, secondary sludge is generally combined with primary sludge before final pressing.

2.2.2 Characterization of sludge

The characterization of sludge in the literature has concentrated upon those factors that best describe the toxic potential of the effluent stream after treatment, or upon accumulation of toxic elements within the sludge itself. Thus, significant works have been published examining characteristics of the treated effluent in terms of biological and chemical oxygen demand (BOD and COD), total suspended solids (TSS), and levels of trace elements (including heavy metals). Other studies have examined the accumulation of toxic chemicals within the sludge, in the form of dioxins or heavy metals.

Effluent toxicity

The initial studies in characterization of effluent have set the tone for most following work. In the mid-eighties, there were problems with high levels of total suspended solids (TSS), which would not meet the guidelines then being considered within the USA for emissions. These findings led to greater control over the pulp and paper wastewater treatment lines, which is what we see today (NCASI 1986). Since the late 1980's, there have been significant reductions in the relative amounts of BOD and TSS present in pulp mill effluent, although the absolute production of waste has increased in accordance with the establishment of new installations.

At recycling plants without deinking operations, effluent flows have decreased from an average level of 10 m^3 to between 7 and 8 m^3 per metric ton of paper product. At recycling plants that have deinking operations, flows have decreased from 70 m^3 to an average of 60 m^3 per metric ton of product. BOD levels in 1988 were 11 and 64 g/T of product in recycling and deinking mills, respectively. TSS levels in 1988 were 8 and 234 g/T of product in recycling and deinking mills (NCASI 1991).

Recycling has a negative effect on BOD; it is reported that BOD is increased by 0.57 kg/T of product for every one percent increase in the use of non-deinked recovered fiber (NCASI 1994).

Trace elements in sludge

An early study by the NCASI in 1984 measured nutrient levels in primary and secondary sludges, as well as the presence of heavy metals including Cr, Cu, and Pb, and other trace elements such as Al, Fe, Mn and Na. In these early studies, it was found that pulp and paper sludge was quite similar to municipal sludge in general composition (NCASI 1984b). A similar investigation found traces of P and Ti in primary sludge from a groundwood operation. The presence of Ti can be attributed to the use of TiO_2 in the papermaking stage of the operation (Genthe et al. 1993). Another study carried out an analysis of trace elements including Pb, and found that most of trace elements were beneath the level of detection in the effluent or the final sludge material (Badar and Cutbirth 1993).

It is commonly assumed that deink sludges may be more dangerous than other sludges due to the high proportion of ink contained within this material. Inks in the past have used such heavy metals as Zn, Pb, Cu, Cr, Ni, Hg, Co, As, Se, Sb, and V. With changes in ink technology, however, only a few of these metals (Zn, Pb, Cu, Cr) are commonly found in printing inks today (Raitio 1992). Of these metals, chromates are slowly being phased out of production, as they are found to be carcinogenic. The levels of heavy metals in deink sludges have been shown to be very low (Miner and Gellman 1988).

It has been shown that filler materials used in paper production may contain Pb, Cr, Ni and Cu in trace amounts. Deinking chemicals, such as sodium hydroxide and sodium silicate, also may contain trace impurities of heavy metals (Raitio 1992). These chemicals all may be present in sludge, and can usually be traced back to the operations within the mill. Levels of these elements, however, were found to be beneath toxic thresholds.

Chemical compounds in sludge

Many studies have examined the possibility that environmentally dangerous compounds may be present in sludge. One study investigated chemicals such as chloroform, phenol, toluene, trichloroethylene, pentachlorophenol, and PCB 1242. Another examined the presence of sodium salts. These chemicals were all clearly present in the process, having been either present in the feedstock or introduced during the pulping or recycling process. It was found that many of these chemicals could not be detected in the effluent or final sludge material. Of those chemicals present, sodium salts were found predominantly in sludges produced from a chemical pulping plant (Brunner 1992). In many instances, chloroform was the compound found in the greatest concentrations. This is due to the introduction of chlorine during a bleaching stage. Since the publication of this study, chlorine has been greatly reduced as a bleaching agent and thus, the amounts of chloroform expected should be greatly reduced as well (Badar and Cutbirth 1993). These results confirm other findings, which indicate that bleaching operations tend to produce sludge high in chlorinated compounds, while non-bleaching operations produce sludges dominated by phenolic compounds (NCASI 1990).

The presence of cyanide in sludge has been investigated. Concentrations of this chemical were always non-detectable or less than 20 μg/L (NCASI 1991). Similarly, this study showed that PCB levels in sludge are usually below the level of detection (0.5 ppb).

In surveys of the leachates derived from combined primary and secondary sludge, levels of most compounds were not found to be hazardous. Only phenol, toluene, cresols and bis(2-ethylhexyl)-phthalate were found consistently (NCASI 1992, NCASI 1989). One interesting finding indicates that the presence of phenol in mill effluents is not always due to the addition of chemicals. It may be directly related to the wood chemistry of the fibre being pulped. In one Canadian mill, the presence of elevated trace levels of phenol was found to be directly related to the *p*-hydroxybenzoic acid content of the wood (Shariff et al. 1989).

In some studies investigating sludge and effluent chemistry, the purpose is not to identify those elements that might be dangerous after disposal, but those that would upset the biological activity within an activated sludge treatment. Some paper additives, such as dyes and solvents, may be toxic to the bacteria used to treat effluent, and thus may disrupt the effectiveness of treatment (Keech et al. 2000).

It has been shown that sludge produced at virgin, recycling, and deinking operations all tend to test superior to municipal wastewater treatment sludges. Paper-related sludges demonstrate measurable hazardous materials at less than 5% of the corresponding hazardous waste thresholds (NCASI 1991, NCASI 1990).

Macro chemistry of sludge

Most testing of effluent and solid waste generation has focused upon toxicity, and because of this, few studies have reported on the actual macro chemistry of the sludge. One group of polymers present in sludge that has generated a great deal of interest is the resin-fatty acids (RFA). These compounds are considered important because they may interfere with the culture of anaerobic bacteria. It has been shown that of the resin acids, dehydroabietic acid is the most common in the effluent, discharging at a rate of approximately 0.26 kg/MT. Of the fatty acids, linoleic and oleic were measured at 0.064 and 0.05 kg/MT respectively (Werker and Hall 2000, Lo et al. 1994a, Lo et al. 1994b).

All sludges contain high proportions of inorganic material. It has been shown that ash contents in sludge can vary from 15% (in groundwood sludge) to over 50% (in deink sludge) of dry sludge solids (Raitio 1992).

Inter-mill variation in sludge chemistry

Very few studies have examined the chemistry of the woody fraction of sludge, and even fewer have commented upon the variation in wood chemical components from mill to mill. One Soviet study did examine levels of cellulose in sludge from a variety of mills in what is now eastern Russia. The researchers found variations in holocellulose fractions that ranged between 1.8 and 30% of total dry sludge solids. The levels of cellulose were found to be lower in paperboard mills (between 0 and 11.4% of total sludge solids). In an integrated pulp and paper mill, cellulose levels varied between 19 and 43% of total sludge solids. No data existed for recovered paper mills at the time of writing (Igantov and Evilevich 1988). While interesting, this study lacked precision in identifying mill types, sampling techniques, and testing methods used.

A second study by Genthe et al. (1993) examined the trace elemental composition of sludges produced by the groundwood and Kraft processes. It was found that K, P, Fe and Ti are present only in sludges produced by the groundwood process, and are absent from the by-products of the Kraft process. This difference reflects the processes used to create each sludge type. Typically, chemical pulping processes will remove much of the extraneous material found within wood, as the chemical digestion leaves little opportunity for material to remain. Thus, the chemical liquor takes up most trace elements during the pulping process, which leaves minimal amounts of trace elements to be detected in the waste stream. At the same time, the groundwood process leaves behind these elements, allowing them to be found in the waste stream.

It is clear that there is variation in the physical and chemical composition of sludges from different processes, but the nature of this variation has not been addressed satisfactorily in the literature.

2.2.3 Dewatering

Dewatering is the process of removing water from the sludge as generated. This step takes place after sludge collection and combination of primary and secondary sludge in the sludge chest, but before disposal of the material.

Mechanisms for dewatering

The first stage in dewatering is often a mix tank, which holds sludge for a retention time of not less than 10 minutes, and often up to several hours. This tank is where primary and secondary sludges are mixed together. Residence time must be sufficient to ensure a good mixture of the two sludge types, which in turn ensures good pressability (Kenny et al. 1995).

If the secondary sludge is at too low of a consistency, the mixing of the two sludge types will produce a material that is very high in moisture. Thus, a pre-thickening stage is often inserted to raise the solids content of the secondary sludge. A number of physical solutions can be applied, such as gravity settling, centrifugation, a gravity belt, or a rotary screen thickener. Rotary screen thickeners and gravity belts work by drawing the sludge in a thin layer over a screen. These methods may raise the concentration of the secondary sludge to between 4 and 10% (Biermann 1996, Kenny et al. 1995). Screw presses are widely used, and may raise the combined sludge solids content to over 30%. Belt presses are not as effective as screw presses, primarily because the amount of pressure that a belt press can exert is limited by the tensile strength of the belt, whereas a screw press uses a solid plate and is not limited by such factors. The combined sludge solids content achieved with belt presses is normally in the range of 20% (Kenny et al. 1995).

Much of the water that remains in the sludge is not easily removed by physical means. The concept of 'bound' water in sludge has been brought forward on many occasions, and essentially describes the condition where hydrophilic organic surfaces are in contact with much of the remaining water in the material, creating hydrogen bonding between the water molecules and the organic polymers in the material. This bonding creates a colloidal mass that is very difficult to separate. The concept of 'bound water' in sludge was elaborated upon by Vesilind, who described the water remaining in sludge as vicinal water, rather than bulk and interstitial water (Vesilind 1994). Freezing and thawing of the material can be used to break the hydrogen bonding. It has been shown that adding a freeze-thaw stage to the dewatering process has the potential to increase dewatering effectiveness by up to three times, but this procedure is very costly in terms of energy required if the ambient outdoor temperature does not cooperate (Lee and Hsu 1994).

Chemical additions

Typical chemicals involved in dewatering are coagulants and flocculants, which help the solids to combine and thus ease the burden of the press. Coagulants often used are diethylamine, ferric sulphate, polyacrylamide, polyethylene oxide and ferric chloride (Kenny et al. 1995). In order to offset chemical costs, however, many mills actually direct a portion of the fibre reject stream from the pulper into the waste stream. This serves the dual purpose of thickening the sludge and reducing the need for expensive coagulants (Pickell and Wunderlich 1995). In other situations, mills have added sawdust and other waste material in order to achieve the same goal (Wong 1993).

It has been shown that optimum mixtures of different sludge streams can make dramatic differences to the dewaterability of sludge. In one study, the cost for dewatering dropped from $80 to $30/T of oven-dry sludge solids when an optimum mixture of primary, secondary and deink sludge was achieved. This type of optimization can be expected to be implemented in most paper mills in coming years (Harvey and Boulanger 1999).

2.3 Disposal of Sludge

The general practices of the North American pulp and paper industry can be summarized in

Figure 2.3. It is evident from this graph that most of the sludge material is landfilled, and that the material that is not landfilled is almost always burnt or removed for land application. In other words, there is still very little actual recycling of sludge. During the early 90's, individual companies privately owned over 50% of landfills used in the pulp and paper industry. This figure is declining, however, due to increasingly stringent requirements for siting and construction (Glowacki 1994). In the USA, over 85% of sludge is disposed of through landfilling (Amberg 1988).

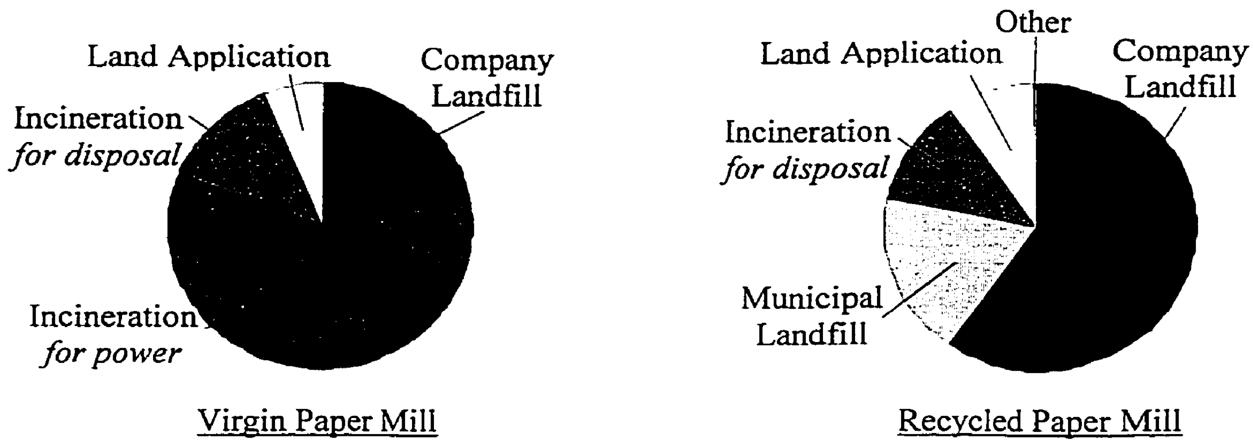


Figure 2.3 Typical papermill sludge disposal practices
Sources: Badar and Cutbirth 1993, Pickell and Wunderlich 1995, NCASI 1991

The very real difference in disposal practices between virgin pulp and paper mills and recycling installations is attributable to process. Recovered paper plants require less energy than do virgin pulping installations; the actual pulping stage in a recycled paper plant is essentially a deragging of existing paper. In addition, most recycled paper plants are located within urban areas, with easy access to large population centers. The feasibility of incinerating large proportions of fibre-rich sludge causes problems in terms of emissions control. In urban centers, much more strict laws apply towards colour and odour emissions.

Landfill

Landfill is the most commonly used disposal technique for sludge. The most important criteria that can limit this route for disposal is the presence of trace chemicals, such as PCB's, which may leach into the water table beneath the site. Modern landfills are designed with the objective to minimize these contacts. Very few problems have been noted with leachates or with gas production in landfills that deal with papermill sludges (Miner and Gellman 1988). Better construction techniques, including lining of landfills with dense clays or with a synthetic material such as high-density polyethylene, further reduces the threat of leaching (Maule et al. 1993).

The availability of landfills is currently decreasing as the environmental implications of burying solid waste are realized. As a result, charges for existing landfills are rising, and new landfills are becoming more difficult to site. As planning and operation costs for individual landfills become more expensive, mills are finding it prohibitively expensive to construct their own facilities. Instead, it becomes economical to pay the tipping charges at existing sites, which are normally municipal or large-scale industrial installations (Coburn and Dolan 1995). This puts additional pressure on those sites that are in common usage, as papermill wastes can be quite bulky. Today, the typical planning time for a landfill can last up to a decade, and require extensive public and government consultation (Harrison 1989). The future use of this option may be very limited (Raitio 1992).

Occasionally, combined primary and secondary sludges are used as the day-to-day cover material in an operating municipal landfill, or as a capping material to close a landfill when the site is taken out of service. This practice is more widely followed in the United States than elsewhere in the world. In practice, this is a win-win scenario, as the sludge is landfilled while replacing some of the earth normally used to cap the daily inputs. The NCASI has investigated the use of sludge as a capping material and has found that the material performed as well as or better than the clay barriers that are traditionally used (Wiegand and Unwin 1994). Hydraulic conductivity, which is a measure of the wicking potential of the capping material, is found to be quite low in sludge and can be reduced further through the addition of coal or fly ash (NCASI 1989). However, the high moisture content and low shear strengths of mixed papermill sludge can be a barrier to the widespread use of this method (Coburn and Dolan 1995, Genthe et al. 1993). In two recent studies, combined primary and secondary sludge was successfully used to cap a landfill at the cease of site operations (Badu-Tweneboah et al. 2000, Malmstead et al. 1999).

The current construction of landfills is such that there is little opportunity for degradation of the material once it has been encased in the fill area. There have been occasions of old landfills being opened and newspapers dating back decades still being legible. Essentially, this means that a landfill can be considered a closed system, with little or no material emissions.

Incineration

Incineration of sludge serves two purposes; it disposes of the material, and it provides heat energy that can be used in the papermaking process. Because sludge is much higher in moisture and ash content, certain modifications to traditional incineration practices must be implemented.

Traditional incinerator grate technology consists of a flat or angled grate, upon which material is placed for incineration. Solid material such as ash can pass through the grate, but if present at high levels will clog the surface and lead to incomplete combustion. Brunner (1992) pointed out that a problem associated with burning sludge on a traditional grate is that the fuel bed must be at a high temperature (>700^{0}C) in order to totally incinerate the organic materials, but that this temperature is high enough to melt the inorganic salts and silica that are found in sludge. Thus, slag develops, which can fill the hearth of a multiple-hearth furnace (Brunner 1992). When sludge is combined with high ratios of bark, incineration is possible, but the amount of bark required is very large which reduces the effectiveness of incineration as a disposal option (Kraft and Orender 1993, Douglas et al. 1994). Modern incinerators use fluid bed technology. This type of furnace uses a bedding material of gravel or stone, which is heated at the base of the furnace. The absence of a traditional grate makes it more difficult to clog the oven, allowing for better combustion of high-ash material. A modification on this is the circulating fluid bed furnace, which continually rotates the bedding material, further preventing build-up of slag at the bottom of the furnace (Kraft and Orender 1993, Brunner 1992). Finally, bubbling bed technology, where air is bubbled through the bed of the furnace, is shown to perform the best with sludge (McCulloch and Sweeney 1994, Kraft and Orender 1993).

The heating values of deink sludge are modest. The effective heat values for the deink sludge from three Scandinavian plants, for instance, ranged from 6 up to 14 MJ/kg dry solids (Raitio 1992). If mixed with large amounts of bark or lignin, the effective heat value can rise to as much as 26 MJ/kg dry solids (Smetanin et al. 1988). By way of comparison, typical woods have effective heat values ranging between 17 and 21 MJ/kg dry solids. In addition, sludge has a very high ash content, which requires a fluidized bed system as opposed to a simple grate boiler. Thus, there is a capital cost to using sludge as a heat source. This makes it difficult to measure the savings attributed to burning sludge in terms of energy, but one claim puts the total savings at 3000 m^3 of heating oil per year (Raitio 1992).

Another problem with incinerating sludge is the need to reduce the moisture content of the material before combustion. A great deal of heat is necessary to burn sludge when it displays high moisture content. The economical moisture content levels vary between 28 and 50% solids. In Figure 2.4, the heat produced or required to combust a metric ton of sludge is shown. The negative values of heat required indicate an overall gain in energy, while the positive values require excess heat for combustion (Pickell and Wunderlich 1995).

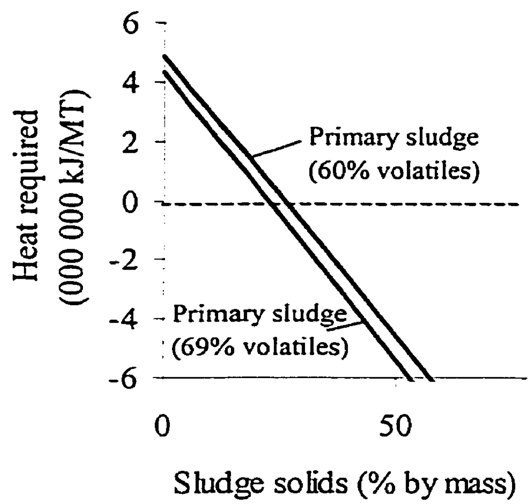


Figure 2.4 Heat required to sustain combustion of sludge
Source: Pickell and Wunderlich 1995

One option for indirect combustion of sludge is the production of ethanol. At least one study has advocated producing ethanol from the sugar-rich primary sludge (Wiegand and Unwin 1994). By fermenting the derived sugars of sludge with a strain of *Escherichia coli*, ethanol can be produced at a rate that is promising for industrial applications (Ingram and Conway 1988). However, it is necessary to use very sugar-rich sludges, preferably containing fibre derived from chemical pulping. The most likely scenario for efficient ethanol production from sludge would involve a separate operating company importing and refining waste from multiple paper mills (Glowacki 1994).

Possibilities for pyrolysis of sludges or supercritical water oxidation have been explored, but have never proved economical (Wiegand and Unwin 1994). In studies conducted between 1988 and 1993, incineration costs have been cited between $50 000 and $75 000 in capital expenses and $15-20/dry ton in operating costs (Glowacki 1994).

As an alternative to incineration within the mill, sludge can be pelletized for sale as an alternative fuel source. It is necessary to dry the sludge to at least 20% moisture content; in order to do this, non-recyclable paper is often added (Wiegand and Unwin 1994). The effective heat value associated with pelletized sludge is modest when compared to woods, in the range of 15 MJ/kg.

Land application

The earliest studies for land application of sludges took place in the early 1980's. It was found that pulp and paper sludges were well suited for land application. The main problem identified in the earliest trials was the low fertilization value associated with the sludge (NCASI 1984a).

Today, pilot projects for spreading sludge on land are very common. Pickell and Wunderlich (1995) have reported on several different endeavours within North America. Pulp and paper installations in Seattle WA, Vancouver BC, and on Vancouver Island BC have all initiated pilot programs within the last decade in which mixtures of pulp and paper mill sludge is mixed with municipal sludge and applied to the soil. The normal locations for applications are company-controlled areas, such as tree farms, or marginal farmland that has been planted over with seedlings. Costs per hectare vary, but initial reports place the costs at about $50/ha. Similar programs have been reported in Asia, Europe, and Russia (Kenny and Yampolsky 1995). However, little data is available from these trials on the usefulness of the final material as a fertilizing agent.

Sludge is very carbon rich, but tends to have very low levels of nitrogen or phosphorus that would make it a good candidate for fertilization. It has been shown in studies that sludge applications in excess of 50 MT/ha can actually decrease yields of some plants. However, the depressive effect of the sludge seems to be neutralized after about 10 months in the field

(Vasconcelos and Cabral 1993). The causes of this depressive effect are thought to be the high C/N and/or C/P ratios found in the sludge. A further conclusion of this study is that repeat applications of sludge can lead to pollution problems later on, most notably an increase of exchangeable sodium content. Finally, no heavy metal pollution was found or expected with sludge application (Vasconcelos and Cabral 1993, Miner and Gellman 1988).

One study examining yields of Bermuda grass on mine soils treated with primary sludge at rates of 56 000, 112 000, and 224 000 kg/ha. However, the yield of Bermuda grass was very poor, and in fact was restricted by the application of sludge at higher rates. It was found that it was necessary to combine the treatments with fertilizer. When the sludge was combined with fertilizer, yields were increased by a factor of ten (Feagley et al. 1994).

When the primary and secondary sludge streams are separated and applied individually to soil, it was found that secondary sludges, due to higher nitrogen and phosphorus content, are actually more suitable for application. Values of nutrients vary, but one reported range of secondary sludge values are 3% N, 1.5% P, and 0% K (Pickell and Wunderlich 1995).

In one recent study, the growth and yield of lodgepole pine (*Pinus contorta* Dougl. ex Loud.) and white spruce (*Picea glauca* (Moench) Voss) grown on sludge-treated soil were measured. Primary and secondary sludge mixed in the ratio of 1:2 was applied to marginal forestland at a rate of 80 T/ha per year. The resulting seedling growth showed significant increases of up to 250% in both height and diameter gain, as compared to control sites (Macyk 1999).

In examining the suitability of sludge for soil application, the possibility of groundwater contamination has not been ignored. In order to determine whether groundwater contamination was occurring, the application of secondary sludge to a forest ecosystem was studied. It was found that an application of 32 T/ha did would not produce NO_3-N values greater than 10 mg/L in the groundwater, provided that the water table was $\geq$ 1.6 metres beneath the forest floor. It was suggested that further application, up to 46 T/ha, would not cause groundwater changes exceeding potability standards as long as the groundwater table was $\geq$ 5.2 metres below the surface (Bockheim et al. 1988).

The option of composting mixed sludges and then applying them to the ground is an option that has been pursued by several mills in the USA. This operation can be quite expensive (upwards of $30/ton) and thus economic success is dependent upon market conditions (Pickell and

Wunderlich 1995, Wiegand and Unwin 1994). Recent studies in Canada have also explored this issue and found that even the best-case scenario for sludge composting remained unprofitable given current economic conditions (Arrougé et al. 1999).

The land application of ash after sludge incineration has also been examined. The ash residue from the incineration of wood and sludge at an unknown ratio was deposited on surface soil types. The ash, rich in silica, calcium, and aluminum, was found to have no fertilizer value, but acted as a suitable liming agent to increase the pH of acidic soils (Ohno and Erich 1993).

Recycling

One way to recycle the fibres within primary sludges is to utilize the material as feedstock in another mill. This type of recycling is known as fibre transfer, and it is an economical way to dispose of what was once considered waste. However, the categorizing of the material as waste in some jurisdictions has restricted the potential of this type of recycling, as waste substances require special permits and equipment for transportation (Coburn and Dolan 1995).

Some preliminary work on recycling primary sludge has shown that filtration is effective in recovering fibrous material from the waste stream. A proprietary system developed in the USA that employs a disk filter on the primary sludge stream has been successful in removing 20% of the total sludge dry matter in the form of wood fibres (Moss and Johnstone 1993).

Another way to recycle is to return the primary sludge stream to the fibre processing system. This is commonly used in the paperboard industry (Wiegand and Unwin 1994). In Turkey, a successful operation managed to combine primary sludge with wood fibre in order to produce hardboard. This product, made at a 1:4 ratio, was estimated to save almost $500 000 (USD) per year in wood costs, and a further $150 000 (USD) on electricity costs. However, the cost of wood in Turkey is quite high, and such an operation may not be feasible in North America (Ozturk et al. 1993).

Sludge can be used in the manufacture of new products, including ceramic and building materials, such as cement, bricks and concrete. For combination with cement products, sludge can be added to a cement kiln at a rate of about 2% of the total; or, it can be used as filler or aggregate in cement mixtures, where the presence of sludge can actually raise the strength of the material, although long-term durability of the material has been questioned. Sludge can also be pelletized for use as a fuel source or as bedding or litter for animals (Wiegand and Unwin 1994).

Some investigations have examined the feasibility of blending sludge into animal feed. The carbohydrate and ash content of the material limits the total amount that can be added. For instance, hardwood pulp residue tends to be more easily digestible than softwood pulps, due to the chemical nature of the material (Wiegand and Unwin 1994). Secondary sludge can also be a source of cell protein, which is present in the material due to the fermentation of the fibres within the waste stream. This material can be extracted from the sludge through concentration of the solids in combination with oils. In its concentrated form, the protein has only 1% water and 16% oil. Unfortunately, the process was far too expensive to be attractive to industry (Wiegand and Unwin 1994). At least one commercial operation in this area has failed due to poor marketability (Bellamy 1995).

One problem with recycling fibres from the waste stream is that the remaining sludge becomes more colloidal in nature as the true fibre fraction is reduced. In practice, fibre is often added to the sludge stream in order to improve dewatering (Pickell and Wunderlich 1995). Another problem associated with this endeavour is that lowering the fibre fraction makes the remaining waste significantly less stable as a solid. Genthe et al. explored this issue by measuring the shear strength associated with Kraft and groundwood sludges at various densities. As the fibre fraction of the sludge was reduced, internal shear strength of the solid sludge material declined (Genthe et al. 1993). The loss of stability of the sludge solid has ramifications for landfill design and limits the choices for ultimate disposal of the material. Thus, it would appear that there is a balance in the amount of fibre that can be removed from the material and options of safely disposing of the sludge that remains.

2.4 Sludge Generation

The physical and chemical characteristics of sludge are variable, in that the sludge characteristics of a single mill will vary over time, and the sludges from different mills – even those with similar processes - will exhibit different properties. There are few studies in the literature that detail the range of inter- and intramill sludge variation.

2.4.1 Typical generation rates

In 1993, it was estimated that the global pulp and paper industry removed an estimated 2.3 million dry metric tons of settled solids from their wastewater liquid effluent streams (Genthe et al. 1993). These streams are illustrated in Figure 2.5. After drying, primary sludge may contain anywhere from 30 to 70% moisture, while combined primary/secondary material is generally well over 100% moisture on an oven-dry basis, which effectively doubles the total mass of sludge being generated.

A single mill can produce up to 10 000 m^3 of liquid effluent annually, or about 6000 L per metric ton of product (Kenny and Yampolsky 1995, Badar and Cutbirth 1993). From these liquid effluent streams, a typical recovered paper mill will remove in excess of 6000 T per year of primary deink sludge, or 63 kg of sludge per metric ton of recycled material. This figure can rise to about 240 kg per metric ton of recycled pulp depending on the complexity of the recycling process being used, and particularly upon the presence or absence of deinking technology (Raitio 1992).

The amount of secondary sludge generated at a pulp and paper mill depends mostly upon the treatment type used. It has been shown that production of secondary sludge can be reduced by up to 43% through control of process parameters, including UV and anoxic conditioning (Elliott et al. 1999).

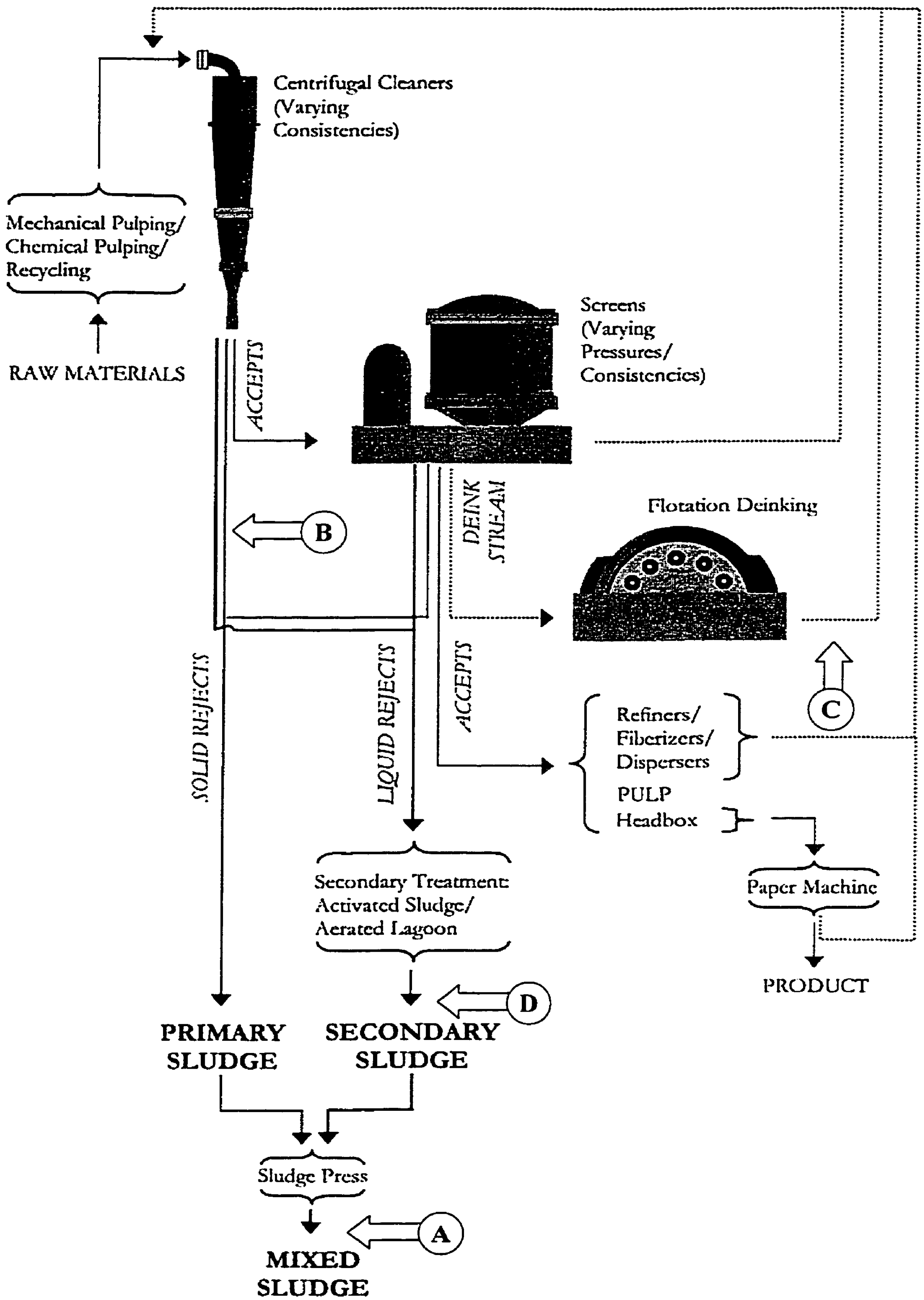


Figure 2.5 Simplified layout of sludge generation paths

A summary of sludge and effluent generation from a recycled paper mill is shown in Table 2.4. This data clearly shows the large proportion of sludge that can be attributed to the recycling process, as approximately 1/3 of the total sludge is generated during the flotation stage. The data also shows the large quantities of water that are used within a paper mill.

Table 2.4 Sludge and effluent production from a typical deink mill

Stage	Sludge *kg/metric ton*	Effluent *L/metric ton*
Pulper	10	2 090
High density cleaners/ coarse screeners	10	
Flotation deinking	70	3 440
Washing and white water clarification		1 250
Fine screening	10	830
Cleaning	60	
Rejects to waste	40	
Purge		6 260
Miscellaneous		830
TOTAL	200	14 700

Source: Badar and Cutbirth 1993

2.4.2 Inter-mill variations

The amount of sludge produced, and the toxicity of the resulting effluent, is related to the type of process used. Pulp and paper mills can be categorized in several ways: mechanical vs. chemical, recovered vs. virgin, etc. A summary of the variation in effluent characteristics and sludge generation rates is shown in Table 2.5.

Table 2.5 Effluent characteristics and sludge generation rates for different processes

Mill type	**BOD** *(kg/T)*	**TSS** *(kg/T)*	**Primary** *(%)*	**Secondary** *(%)*	**TOTAL** *(%)*
Groundwood	0.9	1.9	7.0	1.8	8.8
Semi-chemical	2.0	2.4	2.0	1.9	3.9
Sulphite	10.5	16.0	5.0	2.8	7.8
Unbleached Kraft	1.6	2.6	2.5	0.7	3.2
Bleached Kraft	3.2	5.5	6.0	2.6	8.6
Non-integrated	2.4	2.5	4.0	0.7	4.7
Waste paper	0.32	0.9	4.0	0.7	4.7
Deinking	2.1	3.7	17 - 26.0	2.1 - 2.4	19.1 - 28.4

Sources: Bellamy 1995, Badar and Cutbirth 1993

It is clear from the data presented in the table above that the effluent associated with sulphite mills are by far the greatest polluters, in terms of BOD and TSS. The use of sulphite mills is currently in decline, both within Canada and around the world, and for this reason little work has been carried out to improve the characteristics of mill effluent from the remaining sulphite installations. Interestingly, the effluent associated with waste paper recycling plants that do not involve deinking show the lowest BOD and TSS levels. This type of installation uses the simplest process with the least chemical input of all pulp and paper installations, and therefore these mills have the cleanest pulp effluent by these units of measure.

The variability in effluent chemistry, as described by BOD, TSS, and AOX, has been examined in 24 virgin paper mills in the western Canadian provinces. The study showed that variability in effluent has actually declined from 1980 levels, due to better spill control and sludge management at the mill (McCubbin et al. 1994). This decline in variability does not necessarily reduce the amount of effluent produced, however.

Deink mills are by far the greatest producers of sludge, as a percentage of total paper production. These mills produce more than three times the amount of sludge per ton of product than do other papermaking installations. Examination of this dataset also indicates that bleaching plants tend to produce greater amounts of sludge than do installations without a bleaching operation. The greatest amounts of secondary sludge are associated with sulphite mills, which is again related to the characteristics of the effluent produced from these types of operations.

While the variability in effluent chemistry has declined, the amounts of sludge produced by different mill processes, and the ratios in which primary and secondary sludges are combined, still vary tremendously. One recent study examined the generation of solids from pulp and paper installations across the country, and found that sludge accounts for 23% of all solid wastes generated by the mill, with the largest component of solid waste being wood and bark used for fuel (47%) (Reid 1998).

Table 2.6 Sludge generation and disposal methods for different mill types

Mill Type	Disposal Methodology	Secondary Treatment	A Primary sludge (T/a)[1]	B Secondary sludge (T/a)[1]	Mix ratio (A:B)[2]
BCTMP	Incineration	AS	1 460	13 140	1:9
BCTMP	Incineration	AS	10 950	2 555	4.3:1
BCTMP	Incineration	Zero Effluent	2 190	-	-:-
BCTMP	Landfill	AS	4 380	4 380	1:1
BCTMP	Landfill (Primary)/ Incineration	Anaerobic/AS	10 585	4 015	2.6:1
Kraft	25% Incineration/Power 75% Landfill	ASB	4 745	-	-:-
Kraft	Incineration/Power	AS	1 825	7 300	1:4
Kraft	Incineration/Power	AS	7 300	7 300	1:1
Kraft	Incineration/Power	AS	6 570	2 555	2.6:1
Kraft	Incineration/Power	ASB	1 095	-	-:-
Kraft	Incineration/Power	UNOX	18 250	7 300	2.5:1
Kraft	Incineration/Power	UNOX	18 250	8 760	2.1:1
Kraft	Incineration/Power	UNOX	32 850	9 125	3.6:1
Kraft	Incineration/Power	UNOX	3 650	3 650	1:1
Kraft	Incineration/Power	UNOX	14 600	10 950	1.3:1
Kraft	Incineration/Power	UNOX	18 250	9 125	2:1
Kraft	Landfill	ASB	4 380	-	-:-
Kraft	Landfill	ASB	14 600	-	-:-
Kraft	Landfill	ASB	10 950	-	-:-
Kraft	Landfill	ASB	6 570	-	-:-

[1]Indicates dry solids mass of sludge (at 0% moisture content)

[2]Based on dry solids fraction within the sludge

Source: Pickell and Wunderlich 1995

Table 2.6 lists the generation rates and mixture ratios for 24 virgin paper mills in the western Canadian provinces (Pickell and Wunderlich 1995). Generation rates are controlled by two factors: the amount of paper being produced, and the treatment type chosen.

The data in Table 2.6 indicates that, although average generation rates may normally indicate greater primary sludge production than secondary sludge production, the actual mill practice can vary greatly. The variation is strongest in certain bleaching plants, where the amount of secondary sludge produced annually is much higher than the amount of primary sludge.

2.4.3 Intra-mill variations

The variation of mill sludge characteristics over time is an important question when one considers the usefulness of extrapolating sample data. Published work investigating the intramill variation is almost completely limited to effluent toxicity. It has been shown that virtually all aspects of effluent chemistry are quite variable when measured repeatedly over time. In one study, variables such as pH, Ca, volatile solids, sodium, nitrogen, and sulfate were measured over a one-year period for mill effluents in Ontario. Each of these effluent levels showed significant variation over the sampling period, independent of the mill feedstock or process (Bellamy 1995). However, when variability is considered as relative to actual output levels, conclusions are less dramatic. In the analysis of the effluent of thirteen Ontario mills, it was shown that while one-day variability was quite high, the longer term four-day and thirty-day variability became quite negligible (McCubbin et al. 1994). This observation indirectly indicates that variations in mill sludge characteristics, which may be highly noticeable over short periods, tend to even out over long periods of observation. The use of one-month periods for long-term testing was noted.

Very few studies have examined the physical characteristics of sludge from a single mill over an extended sampling period. One of the few to do so examined the hydraulic conductivity of the sludge material, which has important implications for the use of sludge as a landfill cap or cover material. Variations in the hydraulic conductivity within mills were found to be very low. In one such study, hydraulic conductivity was found to range between 5×10^{-7} and 15×10^{-7} cm/sec (Genthe et al. 1993).

2.5 Modeling techniques

2.5.1 Modeling future fibre use

To anticipate future trends in fibre use, two approaches can be used. The econometric approach examines aspects of supply and demand and makes predictions based on trends in these areas. As such, these models are affected most by social variables, beginning with income and prosperity. Another approach is to analyze absolute trends, and to project these trends into the future. Both of these approaches are commonly used in the analysis of wood supply and future pulp and paper production.

The amount of wood fibre that will be available for pulp and paper fibre is unclear. Supply-based modeling tends to provide a reassuring view of wood supply. Jaakko Pöyry Consulting AB of Finland were contracted to assess the global fibre supply in 1995; they concluded that there is ample wood fibre for the next two decades (Jaakko Pöyry 1995b, Jaakko Pöyry 1995a). A similar study carried out in the same year anticipated no shortage in wood supply, but rather a shift in the type of wood available from large, old-growth timber to second-growth wood and smaller logs (Sedjo and Lyon 1995). The Global Fibre Supply Model, carried out by the FAO at the behest of the forest products industry in 1998, predicted similar scenarios (Bull et al. 1998a). Each of these predictive models, although conducted using different parameters and modeling techniques, predicted that the current trend of increasing production in the tropical and semi-tropical regions of the world would increase as time goes on. In addition, because these models were global in scale, they tend to gloss over deficits or surpluses in wood supply at the local level.

Econometric modeling of the supply and demand for paper and paper products tend to be more pessimistic than general models for wood supply. Two studies, each carried out in the late 1990's, anticipated a large gap between demand and supply for wood products (Nilsson 1996, Apsey and Reed 1995). These models, however, reflect a period of consumer growth that is unequaled in history, and may in fact overestimate the potential of the marketplace (Chipeta 1997). Furthermore, while econometric modeling may be accurate in reporting increases in pricing and availability of goods, it is not as effective at predicting absolute production or supply, as it relies upon economic rather than absolute limits. The Global Fibre Supply Model included a working model of paper production, consumption, and recovery that is based on factors related to wood supply and population dynamics (Mabee 1998, Mabee and Pande 1997, Mabee 1998). This model is more effective at predicting the actual trends, and from the years 1980 to 1995 could map 95% of global production of paper and paper products with a correlation value of over 90%.

Even short term estimates of future trends in pulp and paper production show shifts from the traditional power base of North America and Europe. When looking ahead to 2004, one study predicted that the American share of global pulp and paper production would fall from 29 to 27%. This decline comes about despite predicted growth in the paper and paperboard sectors (Stanley 2000). These trends are indicative of the growing importance of the Asian market to the global pulp and paper industry.

2.5.2 Modeling carbon budget

Modeling the carbon budget of the forest products industry has not yet been widely addressed in the literature. Rudimentary models that attempt to describe the forests relationship with carbon storage and emissions have been constructed in the last few years. Most of these studies concentrate on the ability of trees to uptake carbon, and then remove any carbon that the tree might emit during its lifetime. Equation 2.1 provides one such model of forest carbon budget (Breymeyer et al. 1996).

Equation 2.1 $$C_{veg} = A - R_{wood} - R_{leaf} - R_{root} - D_{wood} - D_{leaf} - D_{root}$$

where
C_{veg} = annual accumulation of carbon in vegetation
A = net daytime canopy photosynthesis by the over- and understory vegetation
R_x = respiration rates, for wood, leaf and root respectively
D_x = amount of detritus produced, for wood, leaf and root respectively.

In this equation, any use of fibre from the forest must be considered as a debit under D_{wood}, without any consideration for the final use of these fibres.

More complicated models can address the total value of the land, in terms of it's potential for carbon sequestration is given in Equation 2.2 (Hoen and Solberg 1997, Johansson and Löfgren 1985).

Equation 2.2 $$C_{land} = \left[\int_{n=0}^{T} f'(n) \cdot p_1(n) \cdot e^{-r \cdot n} dn + \int_{m=0}^{T+d} g'(m) \cdot (-p_1(m)) \cdot e^{-r \cdot m} dm \right] \cdot (1 - e^{-rT})^{-1}$$

where
C_{land} = annual accumulation of carbon taken up by the forest landscape
f'(n) = annual assimilation of CO_2 in a stand n years after regeneration
pl(n), pl(m) = the marginal value of atmospheric CO_2 reduction at the corresponding point of time (n) or (m)
r = real rate of discount
g'(m) = annual emission of CO2 from a stand m years after regeneration
d = decay lag, or the time taken from harvesting until total decay of all products

The decay lag varies dependent upon the product. The authors of this study accorded pulp and paper products a lag time of between 0 and 5 years. Timber products, such as lumber, were considered to last for up to 200 years (Hoen and Solberg 1997).

In Equation 2.2, forest products are only considered as an emission source, although some lag time is inserted to reflect the ability of these goods to sequester carbon for a limited period. The decay lag term, however, is an entirely arbitrary figure, and reflects no actual scientific data. A significant gap exists in the literature pertaining to the actual role of forest products in the carbon cycle.

2.5.3 Paper production

Most models available in the literature are based upon the econometric model. In this type of model, the supply of material is controlled by demand. The amount of supply can be constrained to real-world limits, but this is not intrinsic in this type of modeling exercise. The modeling tool most often used for this type of exercise is PELPS (Price Endogenous Linear Programming System), which uses linear programming methods to program supply and demand curves under the constraints of supply, distance, and time (Zhang et al. 1993). This type of modeling has been applied in the North American pulp and paper model (NAPAP), the North American solid wood model (NASAW), and the International Tropical Timber Organization's Asia-Pacific trade model (Zhang et al. 1997).

Only a few models existing in the literature have been carried out from a non-economic point of view. The Global Fibre Supply model, constructed by the author as part of a UN team in 1996-1998, is the best example of this type of approach. By examining supply parameters without considering demand as a discrete variable, it is possible to forecast trends that reflect the realities of current supply situations. This type of modeling should be carried out as part of a balanced approach, in which the results can be compared against traditional econometric modeling outputs, and a more comprehensive image of future trends can be created (Bull et al. 1998a).

2.6 Carbon budgeting and the pulp and paper industry

2.6.1 The Kyoto Protocol

Carbon production is becoming an increasingly important problem, one that has been linked to global warming and other aspects of climate change. Currently, 85% of earth's commercial energy needs are supplied by fossil fuels, the burning of which emits a great deal of carbon into the atmosphere. Scientists are faced with the challenge of alleviating some of this pollution.

The issue of carbon generation and sequestration in the forest has been addressed consistently throughout the 1990's. At the 1992 Earth Summit in Rio de Janeiro, the first international convention designed to stabilize greenhouse gas emissions was signed by a majority of nations. However, no clear description of the role of forest products was made in this treaty. The Kyoto conference in 1997 made progress towards generating a blueprint for carbon emission reduction, which is detailed in the protocol of the same name. As in Rio, however, the carbon cycle being considered did not include the role of forest products (FAO 1999a). The Kyoto Protocol, which was passed in December 1997, is scheduled to be ratified in 2002 (Canadian Forest Service 2000, O'Driscoll 2000).

The Kyoto protocol groups together six 'greenhouse' gases: CO_2, CH_4, N_2O, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and SF_6 (O'Driscoll 2000). Until recently, CO_2 was considered the gas of most concern. Recently, media reports have downplayed the importance of carbon to global warming, instead attributing majority of our current climatic instability to other gases, particularly methane and PFC's.

Forests are considered to be one of the most easily manipulated sinks available for sequestering atmospheric carbon. Hence, the Kyoto protocol may have long-lasting ramifications for the global forest industry, including restrictions on fibre sources, limitations on control over fibre supply, and increased tax burdens associated with harvesting operations. Other options for sequestering CO_2 are being explored, including burying emissions underground, or at the bottom of oceans. At this point, however, these options are not considered as practical as changes to current forest practices (Herzog et al. 2000).

One goal of the Kyoto protocol is to stabilize the carbon dioxide concentration at 550 ppm, which is double that of pre-industrial ambient atmosphere, and much higher than our current levels of 360-370 ppm (Herzog et al. 2000, O'Driscoll 2000). The target dates for achieving this goal range from 2008-2012, which provide a 15-year window of opportunity for changes to be made (Canadian Forest Service 2000).

Canada is a willing participant in the Kyoto protocol. In response to the conference, BIOCAP Canada was set up in 1998 in order to bring together researchers from the academic, public, and private sectors to address the issue of carbon generation and global warming. This group put together a 5-year research plan that will elucidate Canada's role in the carbon cycle (Layzell and Leiss 1998). As of writing, however, the future of this group was still uncertain.

2.6.2 Kyoto protocol and the forest industry

Forests are arguably the most easily controlled mass of carbon on the planet, and as a species we have the ability to significantly alter the forest cover of the earth within a very short time. Thus, the potential for forests as a place to sequester carbon is considered enormous, although the long-term potential of forests for carbon sequestration is still open to debate.

Several sections of the Kyoto Protocol have a direct relationship with the forest industry. Under Article 2 of the protocol, each Party or nation agrees to protect and enhance greenhouse sinks, which include forested areas and could affect all forest operations that occur in the signatory nations. Article 3.3 defines 1990 as the baseline year from which changes in forest cover are measured and counted under the agreement, which means that past practices carried out by industry may come under scrutiny. Finally, Article 6 provides a mechanism by which carbon credits and debits can be transferred from country to country, and essentially gives the legal permission for systems of carbon taxing to be implemented (FAO 1999a). In order for carbon taxing to work, an understanding of the true life cycle of forest products must be achieved, and the ultimate disposition of forest carbon must be assessed.

There has been some progress made towards implementing the ideals of the Kyoto protocol. The Canadian government, for example, has organized the Framework Convention on Climate Change, which states that anthropogenic production of greenhouse gas should be limited, while all processes or activities which actively take up greenhouse gases from the atmosphere should be protected and enhanced (Environment Canada 1998). In some cases, the forest industry is singled out over competing resource-based practices. For instance, forest soils are considered as sinks for carbon, while agricultural soils are not. The implication here is that forest practices might require more stringent carbon accounting in the future.

The 'Kyoto forest' is the term affixed to the amount of land that must be managed for carbon sequestration in order to meet Kyoto Protocol commitments. However, this term has not been fully defined; for instance, it is unclear how reforestation, afforestation and deforestation areas are to be counted, and the role of forest products in carbon balance equations is still unclear (Environment Canada 1998). In the long term, the Kyoto forest should include most of the managed forest within a country.

The ability of forests to sequester carbon is not fully understood. Great variations can occur depending on the species composition and location of the forest. Most conventional wisdom tends to view the forest as a sink for carbon. While this may be true for young forests, we will see that it may not apply to the mature forest system. Estimates first released in 1998 by the BIOCAP initiative show that the forest carbon cycle, far from being a clear sink for atmospheric carbon, is actually fairly balanced in terms of CO_2 sequestration and release (Layzell and Leiss 1998). This is shown clearly in Figure 2.6, where the Canadian forest carbon cycle is shown. It is known that trees take up a great deal of carbon early in their lifespan, but that this amount decreases as the trees mature. It has been shown that the net productivity both above and below the ground level tends to peak around the point of canopy closure, and afterwards suffers a serious decline (Breymeyer et al. 1996). This tends to translate into a net carbon uptake of close to zero.

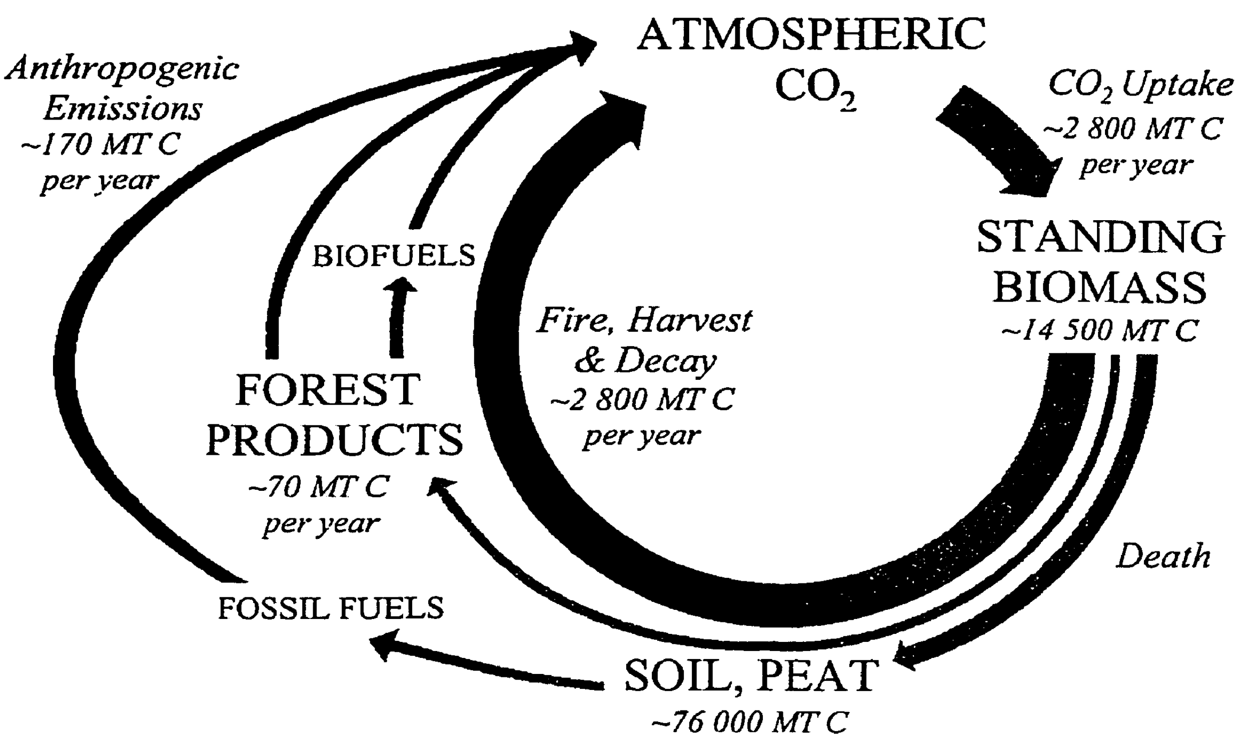


Figure 2.6 Simplified estimate of the Canadian forest-related carbon cycle
Source: Layzell and Leiss 1998, Cannell 1995

Some authors have speculated that Canada's forests shifted from being a carbon sink to a carbon source between 1970 and 1989 (Environment Canada 1998). Changes in disturbance regimes, including climate change and increased harvesting levels, may be changing the ability of the forest to sequester carbon. Analyses have shown that there has been a great deal of carbon lost over the past thirty years in Canadian boreal forests; this is due to an increase in disturbance impacts and reflects the unsuitability of using past measures of CO_2 uptake as a measure of future controls (Kurz and Apps 1996). To paraphrase, changes in carbon emission levels from Canadian forests may be a reflection of the maturity of these forests, which in turn may reflect changes in forest growth that are related to fire suppression or harvesting patterns. This is closely related to findings in the tropics, where older, mature forests do act as net sinks of carbon, but where the carbon uptake is being threatened by a variety of factors, including logging, climate change, and fragmentation (Phillips et al. 1998).

Canada's forest products are theorized to sequester close to 40% of the carbon being currently released by its population through fossil fuel consumption. This figure, however, may be influenced by the amount of land that has been fire damaged and is in recovery state (Cannell

1995). In this respect, Canada is more fortunate than most countries, which lack large forest area that may act as carbon sinks.

One thing that is almost universally agreed upon is that all forests do uptake carbon to some extent, particularly during establishment and juvenile growth. Even urban forests, upon maturity, are capable of sequestering between 10 and 20 MT/ha of carbon, with estimates in Chicago being in the 14 to 18 MT/ha area (Nowak 1994). The amount of carbon a forest is capable of sequestering can vary by up to 1.4 MT/ha per year, due to changes in the length of the growing season, the average cloud cover, the snow depth, and the amount of drought (Goulden et al. 1996).

The age of the forest at harvest also makes a great deal of difference. When forests and forest plantations are compared, it is shown that the maximum amount of carbon stored in a plantation between planting and harvesting is only a third of the carbon stored in a forest at maturity, a figure that can be related directly to the very young age of most forest plantations at harvest (Cannell 1995).

2.6.3 Forest products and the carbon cycle

As was stated in the previous section, forest products have not yet been defined under the Kyoto protocol, and calculations made regarding the protocol do not yet take into account products that are currently in use and in landfills (Environment Canada 1998). There are a few major schools of thought in regards to forest products biomass. One is that the biomass being harvested from forests and turned into products is replacing older forest products made from older biomass, and that all the carbon contained in the forest product is released into the atmosphere. This contradicts one scientific fact, which is that most carbon remains in landfills for a very long time due to the construction and design parameters currently in use (Micales and Skog 1997). Under this school of thought, the emissions related to biomass harvesting and disposal is considered static, and therefore not a major concern under the agreement. It has been noted, however, that the appropriate accounting of forest products and their emissions could become critical, should these activities come under the authority of the Kyoto Protocol (Environment Canada 1998). Others take the approach of discounting the carbon in forest products as being immediately released, rather than being a dynamic part of the carbon cycle of the forest (Kellomäki and Karjalainen 1996).

An opposing view is that forest products can be considered a net sink for carbon. It is theorized, as forests are rotated through multiple harvests, the amount of carbon stored in products, as well as in the litter pool, etc., can appreciably grow (Cannell 1995). It has been shown that, in the case of short-lived wood products (i.e. surviving less than 10 years), more carbon would be sequestered if the forest were allowed to stand indefinitely. However, as product age increases from 10 to 50 to 150 years of age, the amount of carbon being sequestered in the forest products shifts to the products themselves, rather than the trees (Dewar 1990). Further work by Cannell has shown that the amount of carbon stored in forest products, trees, and soil increases as the fraction of carbon in the trees is increased. Essentially, converting fast-growing trees into long-lasting products after achieving maximum growth will sequester the most carbon in any system (Cannell 1995).

Many estimates have been published which place the amount of carbon annually sequestered in forest products as between ¼ and ½ of the total carbon annually sequestered by the world's forests (Kellomäki and Karjalainen 1996, Nabuurs 1996). Some estimates place the amount of carbon sequestered in forest products annually in the 1980's at high as 27 million MT/a, or 72% of all carbon sequestered during the year by the forest (Houghton et al. 1999). These figures, if accurate, represent anywhere from half to a tenth of the total amount of carbon currently sequestered in forested lands.

Recycling has been considered as a potentially good way in which to increase the usefulness of wood products as a carbon sequestering material. By recycling, the amount of new wood needed is theoretically reduced, and the useful lifespan of the existing fibres is extended. One study has found that different types of wood, and the products created from them, have different potentials when considered as candidates for recycling. Recycling imparted a net increase in carbon sequestering ability of approximately 29% for most hardwoods, 73% for spruce, and 167% for poplar (Nabuurs 1996). The study did not consider the energy required recycling the material, nor was any mention made of waste streams and the implicit reduction they may have upon these figures.

2.6.4 Sludge and the carbon cycle

Using waste materials, like sludge, to help sequester carbon is an issue of key interest. If landfilled, the material itself can be considered a sink for carbon. Recycling sludge in a useful capacity can also offset current CO_2 emissions. By reusing the material as fertilizer or fuel, value is added to the waste stream, but also reduces the overall impact of fertilizing and/or energy production options by reducing the amount of CO_2 that is emitted into the atmosphere. This is completely rational, given the normal practice of modelers to relegate all forest products and associated streams to the 'emissions' side of the equation. One study in Sweden found that by applying liquid wastewater to a Norway spruce plantation, the growth of the trees could be increased by up to 50-55 T of dry mass per ha over a six-year period (Nilsson 1997).

Using biomass for energy production is a viable way to reduce the impact of the pulp and paper industry on the overall carbon cycle by lowering fossil fuel requirements. There are some potential problems that are associated with this approach, however, including excess pollution generated by combusting wood grown in a polluted environment. When wood grown in the heavily polluted Eastern Bloc country of Poland was incinerated under controlled conditions, heavy metals, including cadmium, were found within the ash component collected in the cyclone. A solution to this problem has been proposed, but little follow-up work has been done (Narodoslawsky and Obernberger 1996). It may be possible to use incineration of waste to collect heavy metals from incoming wood streams, providing the industry with a way to 'clean' the environment of these heavy metals and effectively remove them from the active ecosystem.

2.6.5 Carbon taxing

Carbon taxing is proposed as one way in which the impact of carbon cycle assessment can be lessened, at both the national scale and for individual forest product companies. One possible solution to the buildup of greenhouse gases is to implement a carbon taxing system, whereby any practice that produces carbon emissions is penalized, while non-polluting industries are rewarded. This is closely followed by the idea of carbon credits and debits which could be put into practice through a system of trade (O'Driscoll 2000). Under a carbon-taxing scheme, a company could earn credits for maintaining a large forest base, or for creating excess recycling programs. Debits could be assigned to companies who do not follow through on regeneration and afforestation programs. These debits and credits could then be traded to allow companies to optimize their operations, while still meeting requirements for sequestering and releasing carbon.

It has been advised that proposals for a carbon tax must take into account several factors. One, the tax would have to be applied equally to the forest products industry as to the fossil fuels industry, as the degradation of one kilo of forest-sequestered carbon is assumed to have the same impact as one kilo of fossil fuel-sequestered carbon. Two, the tax would have to be applied on a per period basis rather than a one-time only tax at harvest; a one-time tax would provide impetus to increase rotation ages and delay payment of taxes, when this is counter-productive to carbon sequestering (Hoen and Solberg 1997). One effect of carbon taxing is that it will increase fossil fuel prices and shift the supply curve for this commodity upwards. This may increase interest in alternative fuel sources, including biofuels derived from trees (Hoen and Solberg 1997). Ultimately, this may have the unfortunate side effect of increasing prices on wood products, as wood becomes a more valued commodity.

Carbon taxing would affect wood products by pushing the optimal rotation age up, as the cost per ton of carbon emitted increases. However, as the discounting rate applied to the tax is increased, the optimal rotation age decreases, in order to limit the impact of long-term payment schedules by reducing interest charges (Hoen and Solberg 1997).

A consistent tax/subsidy policy has to tax all activities leading up to the production of wood products, and subsidize all activities that actively sequester carbon from the atmosphere. The practicality of implementing such a scheme, however, is difficult to gauge (Hoen and Solberg 1997).

In considering a carbon tax scheme, one considerable benefit for the wood products industry would be the substitution of wood products for other products due to the lower level of overall carbon tax due on this type of product. It has been predicted that a type of management for forest resources called 'substitution management' could be devised built on this principal (FAO 1999a, Brown et al. 1996).

2.7 Summary of Literature

Several key gaps have been identified in the literature. No studies have been published which describe an accurate method of separating the woody organic component of sludge from the overall sludge matrix. The chemistry of the woody organic fraction of sludge has not been described, nor has the variation of this chemistry been noted within the literature. Models have been proposed for paper production, consumption, and recovery, but none of the models presented in the literature have concentrated upon supply-side data or upon trends in population-related variables. Finally, the role of sludge in the carbon cycle of forest products has not been described. This thesis will address each of the gaps in the current knowledge in turn.

2.8 Objectives

To reiterate, the principal research question as posed in Section 1.2 is to describe the role that sludge plays in the carbon budget of the pulp and paper industry.

The objectives of the thesis describe the four major tasks that must be completed to answer the research question. Specific objectives are given at the beginning of each chapter. The four major objectives are to:

1. Develop a methodology for characterizing papermill sludge, in terms of inorganic and organic chemical components and fibre morphology;
2. Assess the degree to which sludge chemistry varies over time, and how processes can affect sludge chemistry;
3. Account for the variables which drive paper production, consumption, and recycling at the national level;
4. Extrapolate global sludge production and describe the role that sludge plays in the carbon balance of the pulp and paper industry.

3 Identification and characterization of the woody organic fraction of mixed papermill sludges

3.1 Introduction

3.1.1 Abstract

In order to determine the role that papermill sludge plays in the organic carbon cycle of the forest products industry, the mixed sludge output of six Ontario papermills has been sampled over a four-year period. A methodology to identify and quantify the woody organic material present in the sludge matrix has been proposed and tested. Using this methodology, the physical characteristics of the six sludges have been quantified. The cellulosic and lignosic composition of the woody organic fraction of the sludge has been investigated, as has the inorganic fraction associated with each sludge type. The results of physical and chemical testing were then compared to validate the proposed methodology. The physical properties of sludge fibres were found to be related to the presence or absence of recycled fibres, and showed little correlation to the pulping technique or recovery method employed. The chemistry of the organic fraction of sludge is also related to the presence of recycled fibres, but shows strong variation between different mills that indicates that process can significantly change the characteristics of this material. Correlations were established between the different testing approaches that validated the proposed methodology for quantifying woody organic material within the sludge matrix.

3.1.2 Objectives

The overall objective of this chapter is to develop a methodology for characterizing the woody organic components of sludge within the sludge matrix. The specific objectives of this portion of the study are to:

1. Assess the effectiveness of light microscopy as a means to identify woody organic components;
2. Quantify the proportions of the macro components of sludge, including woody organic material and inorganic detritus;

3. Characterize the woody organic components of the sludge in terms of cellulosics, lignin, and extractable materials;
4. Characterize the inorganic component of the sludge, and;
5. Validate the methodology through comparison of the different approaches.

3.2 Sample collection

3.2.1 Criteria for mill selection

The selection of the mills sampled for this study was based upon several factors, including accessibility, location, product, and process. In order to ensure that the sludge collected was indicative of typical output of the mill, sampling was carried out to meet the following criteria:

1. That each mill had been fully operational for over two years at sampling, without any major overhauls to the operation within that two year framework. This criterion ensured that none of the mills sampled were in start-up mode.
2. That sampling took place on a day of normal operation, without any changes to the waste stream due to downtime, machine breaks or stock spills.

Because of these criteria, several mills that were initially sampled (including installations at Sault Ste. Marie, ON and at Trois Riviéres, PQ) could not be included in the final analysis.

3.2.2 Mill locations and operational parameters

Because every pulp and paper plant utilizes different fibre sources, papermaking machines, and processes, the sludge produced at different mills varies in composition and properties. In this work, the sludge examined was collected over a period of four years, from six different mills that produced a variety of pulp and paper products. These mills were located in central and southern Ontario, with one installation lying on the border of Quebec as shown in Figure 3.1.

Mills A and B are located at the edge of the boreal forest, and are engaged in producing virgin pulp and paper products. Mill A is a Kraft mill, and has a feedstock of primarily black spruce (*Picea mariana* Mill.), although in recent years some poplar (*Populus* spp.) and birch (*Betula* spp.) has been employed. The secondary treatment utilized at this mill is an aerated sludge basin

(ASB) or lagoon system. Mill B chiefly employs the thermomechanical pulping method to produce pulps, but at the time of writing was still operating a single sulphite pulping line that fed a paper machine. The feedstock utilized at this mill is dominated by hardwood species such as poplar, birch, and maple (*Acer* spp.) as well as spruce in order to produce specialty pulps and paperboard. The secondary treatment system used at this installation is an activated sludge (AS) system.

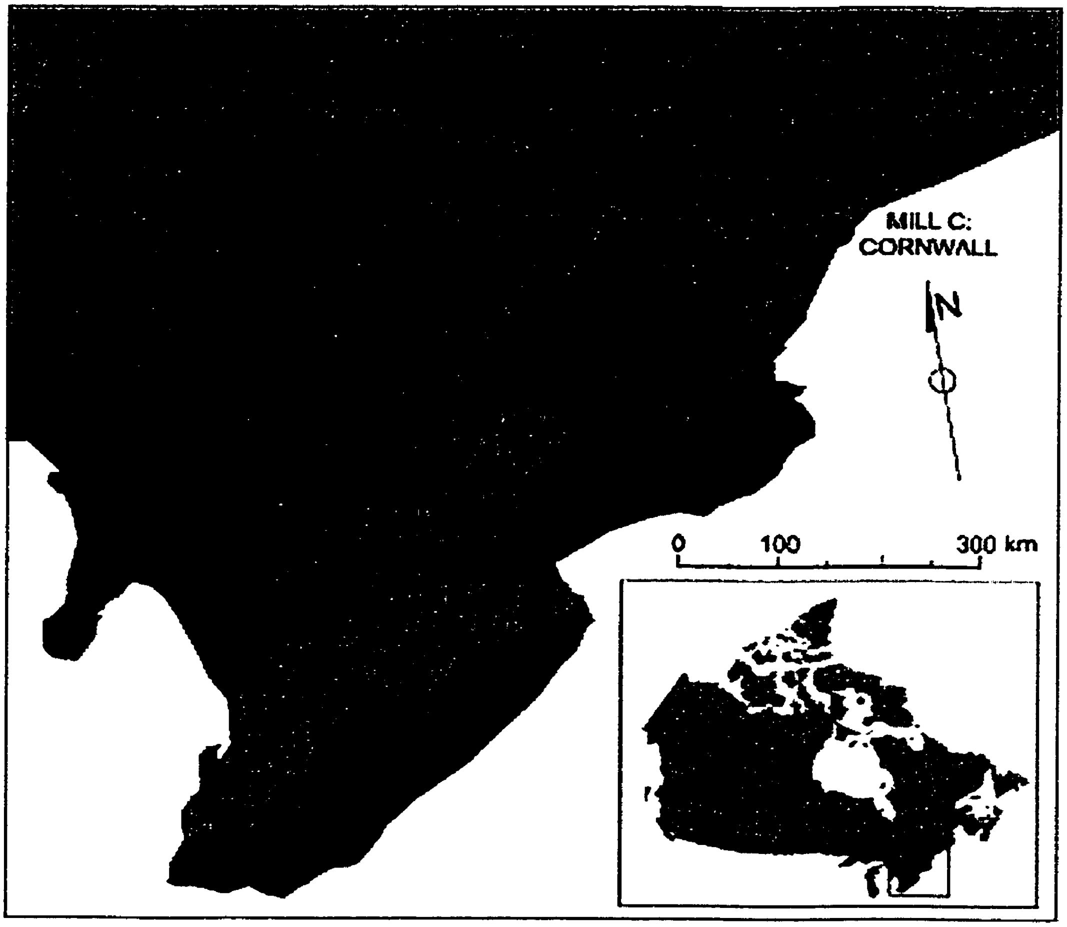


Figure 3.1 Mill locations in Ontario and Quebec

Mills C and D are located on major transportation arteries near the large urban centers of Montreal and Toronto, respectively. Both mills are involved in recycling, but do not employ deinking systems to remove ink from the recovered paper. Mill C uses post-manufacture, pre-consumer wastepaper in combination with some post-consumer waste and some virgin hardwood and softwood fibre to manufacture fine papers. The secondary treatment system used at this mill is an AS system. Mill D is a linerboard mill that utilizes post-consumer waste cardboard and paper to produce linerboard material. No secondary treatment is used at this mill; the wastewater is handled by municipal water treatment systems.

Mill E and Mill F are both recycling plants that incorporate a flotation deinking system. Both mills are located within the Golden Horseshoe region of Ontario, a densely urban region that is centered around Toronto. Both mills utilize old newsprint (ONP), old corrugated and cardboard (OCC), and old magazines (OM) as feedstock; in addition, Mill E also utilizes some virgin fibre. Finally, both mills produce newsprint-grade material for use in the urban newspaper markets of Chicago (Mill E) and Toronto (Mill F). Both mills use an AS system for secondary treatment of wastewater.

The mill characteristics are summarized in Table 3.1 below.

Table 3.1 Sample mill parameters

	Mill A	Mill B	Mill C	Mill D	Mill E	Mill F
Pulping Process	Kraft	TMP/Sulphite	Recycling	Recycling	Recycling	Recycling
Deinking Stage	No	No	No	No	Yes	Yes
Fibre Source	Virgin fibre: *Betula spp.* *Picea spp.* *Populus spp.*	Virgin fibre: *Acer spp.* *Betula spp.* *Picea spp.* *Populus spp.*	Post-manufacture wastepaper, some virgin fibre	ONP, OCC	ONP, OCC, OM, some virgin fibre	ONP, OCC, OM
Primary products	Pulp, printing-grade paper	Pulp, paperboard	Fine paper	Linerboard	Newsprint	Newsprint
Effluent secondary treatment	ASB	AS	AS	None	AS	AS

3.2.3 Sample collection

The sludge collected for the study was taken at the last point before removal from the mill, which in all cases was just after the sludge press. This is denoted in Figure 2.5 as point **A**. In five of the mills, the final sludge output was a mixed sludge, combining the effluent from the primary and secondary treatment streams. In Mill D, only primary treatments are employed. Each sample was actually a composite sample, taken repeatedly over several hours on the actual sampling date.

Each sludge sample was initially high in moisture content (MC), with MC's in the range of 124% to 250% on an oven-dry basis. These moisture contents were determined following the method given in Section 3.3.3. The ratios of primary to secondary sludge were obtained from speaking to mill operators at the time of sampling, and are not based upon quantitative analysis. Initial moisture contents, mixture ratios, and dates of sample collection are tabulated in Table 3.2.

Table 3.2 Sludge samples – dates, sludge ratios, and moisture contents

Mill Location	Date(s) Collected	N	Primary/Secondary Ratio	% Moisture *(average)*
Mill A	07/12/1998	1	2:1	250%
Mill B	07/13/1998	1	2:1	124%
Mill C	03/13/2000 ↔ 04/14/2000	15	2.5:1	173%
Mill D	10/19/1998 ↔ 11/28/1998	5	1:0	178%
Mill E	08/24/1996 ↔ 07/12/1999	5	3.4:1	190%
Mill F	10/16/1997	1	3:1	224%

3.2.4 Sample preparation and storage

The samples as initially received were high in moisture and were therefore dried for a period of 14 days in a fume hood. This brought the material into equilibrium moisture content with the ambient laboratory conditions. After drying, fifty percent of each sample was set aside for physical testing. The remaining 50% portion of each dried sample was ground into powder using a 40 mesh screen, as directed in the TAPPI Standard for sample preparation (TAPPI Standard T257 cm-85; TAPPI 1996). The powdered sludge was used for all chemical testing. All samples were kept in a cold room at 4^0C, in order to inhibit fungal development and fibre degradation.

3.3 Methods

The testing methodology can be divided into three major groups of tests, as shown in Figure 3.2. To identify wood fibres within the sludge matrix, light microscopy was used. The preparation of microscope slides was done using standard methodologies described in the FOR454S Laboratory Manual (Balatinecz 1985, Wilson 1954). Chemical testing was carried out as per standards developed by TAPPI (Technical Association of the Pulp and Paper Industry) and PAPTAC (the Pulp and Paper Technical Association of Canada), except where otherwise noted.

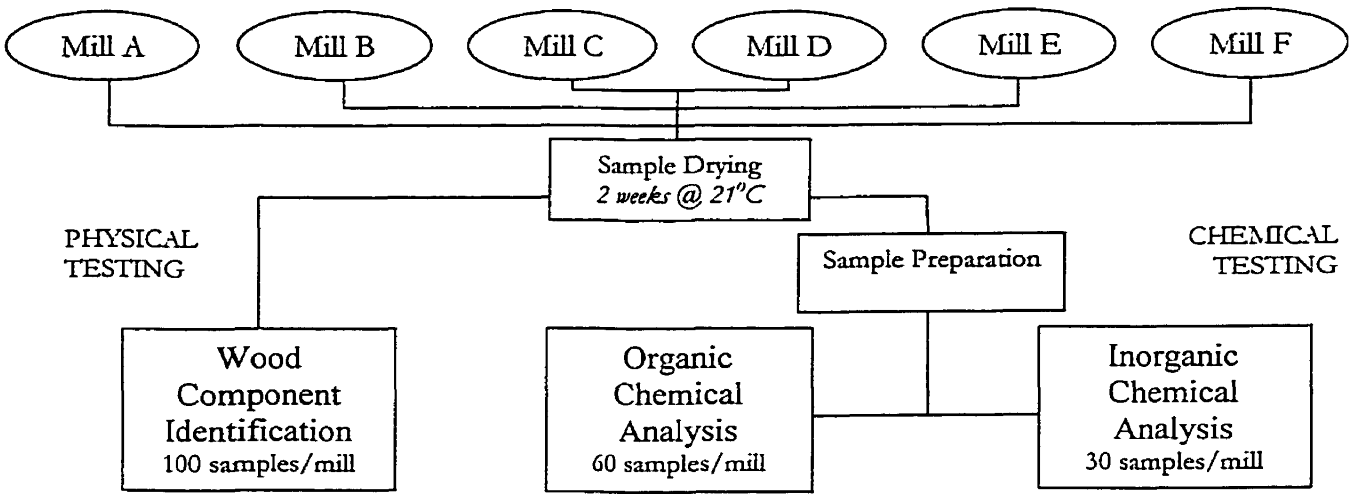


Figure 3.2 Flowchart of testing procedures

3.3.1 Wood component identification

With one exception, the sludges sampled were mixtures of primary and secondary waste streams. The sludge contains many materials in addition to the woody fibres and fine material that is of interest to this study. Thus, a means had to be found to separate the wood components from bacteria, clays, dirt and other detritus found within the sludge stream. This was achieved through photo microscopy. Slides were prepared according to the following methodology. One hundred 5-gram sub-samples of mill sludge were taken. For each sample, the material was placed into a test tube containing distilled water and allowed to soak for 48 hours at room temperature. After the designated period of soaking, the test tubes were shaken vigorously for 10 minutes in order to achieve complete fibre/particle separation. The resulting suspension was immediately transferred via a hollow glass rod (inside diameter of 5 mm) to standard microscope slides. The microscope slides were allowed to dry on a slide warmer at temperatures of 65-70^{o}C. The suspension was kept from overlapping as the slide dried through constant tapping and blowing.

After full drying was achieved, the completed slides were placed in a Coplin jar containing a staining solution of Analine Safranin (1% in 70% alcohol). The slides were allowed to soak in the stain for 2 minutes, after which they were removed and washed in 3 consecutive 85% alcohol solutions until the slides were clear. Finally, the slides were dipped in xylene to clear the material, and cover slips were applied using Permount.

Special measures were taken with the sludge obtained from three of the mills. The recycling facilities at Mill D, Mill E and Mill F all use post-consumer waste, and thus had varying fractions of plastics mixed into the sludge streams. It was necessary to separate the large waste fraction from the smaller detritus and the fibrous material desired for the study. Hence, each sample was filtered through two mesh screens (10 and 20 mesh) and finally through a solvent screen. The solvent screen system consisted of a large beaker (2L), into which the sludge was placed while wet. Water was added to the beaker to bring the suspension to the 1800 ml mark. Finally, 200 ml of toluene was added to create a layer of solvent on top of the water. The mixture was stirred slowly at room temperature for 1 hour, over which time most plastics migrated to the solvent layer, leaving the fibrous and organic material in suspension in the water. The upper solvent layer was then removed, and the mainly fibrous sludge was concentrated. The wet material was then spread out and allowed to dry, as described earlier in this procedure.

Upon completion of the slide manufacture, each slide was examined at x100 magnification on a Riechart light microscope. A representative area on each slide was located and photographed, once under normal illumination and once under polarized light. An example of two matched photographs is shown in Figure 3.3, where the upper portion of the illustration is shown under normal light, and the lower portion under polarized light.

It is obvious from the photographs that the wood fibres are suspended in a mixture of organic fines, other organic material and detritus. In the upper view, the Analine Safranin stain has turned portions of the material red, indicating lignosic or cellulosic material. The lower view, taken under polarized light, shows the crystalline regions as glowing fragments on an otherwise dark slide. These crystalline regions are always associated with a fibre, and reflect the crystalline cellulosic areas within those fibres.

An analysis of these photomicrographs was carried out using a Hewlett-Packard scanner and a custom-developed Visual C++ program. Each photomicrograph was scanned as a TIFF file, and the resulting image was separated by colour on the RGB (Red-Green-Blue) scale. The total area of fibres, fines and detritus was separated from the background, as were all areas falling into the red (normal light) and white (polarized light) areas of the spectrum. Using the total amount of sludge as a baseline, this allowed an inference to be made regarding the total amount of crystalline cellulosic materials (the white areas under polarized light), as well as the total amount of cellulosic and lignosic materials (the total amount of Analine Safranin stained material).

3.3.2 Validation of Testing Method

In order to ensure that area analysis provided an accurate estimate of mass, a simple test was conducted. A mass of cellulose fibre (0.025 g) and secondary sludge (0.025 g) was applied to a glass microscope slide within a 1 cm^2 area on the slide surface. The slides were then stained as described in the section above. A photomicrograph was taken of the slide under both normal and polarized light, and the entire 1 cm^2 area was analyzed using the method described above. This experiment was repeated 20 times in order to build a level of confidence in results, as shown in the table below. It was shown that the amount of cellulose and other organic material found through the test methodology was equal to the amount of cellulose fibre and organic detritus applied to the slide surface. The average amounts of cellulose and organic material found over 20 samples was 50% for each, which is identical to the amount of material applied.

Table 3.3 Results of test methodology validation

Cellulose (%)	Organic Material (%)	Cellulose (%)	Organic Material (%)
51%	49%	51%	49%
55%	45%	49%	51%
52%	48%	47%	53%
48%	52%	48%	52%
49%	51%	48%	52%
49%	51%	47%	53%
50%	50%	52%	48%
51%	49%	50%	50%
52%	48%	50%	50%
52%	48%	49%	51%

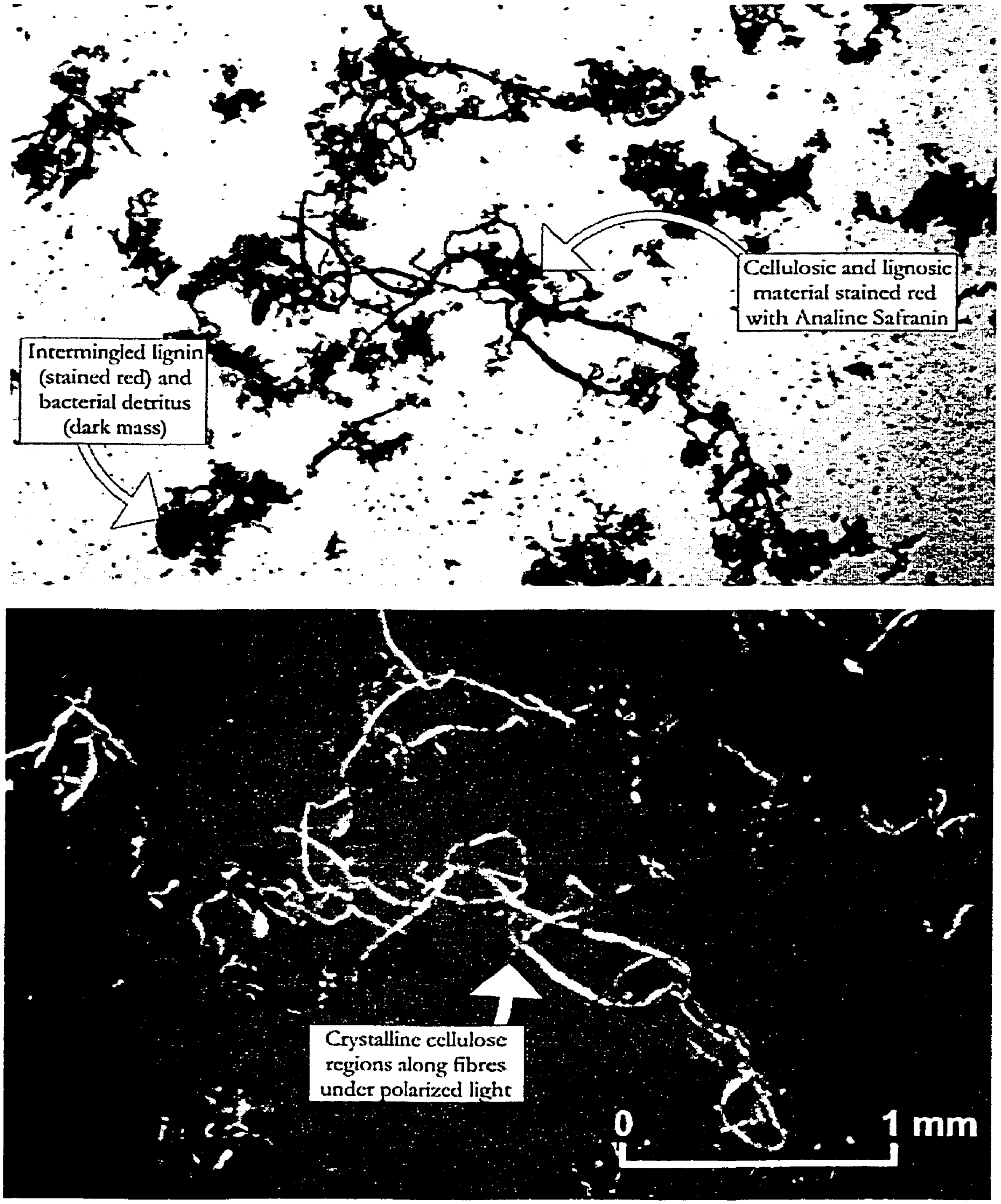


Figure 3.3 Photomicrographs of papermill sludge fibres and detritus (Mill A), stained with Analine Safranin, under normal light (top) and under polarized light (bottom)

3.3.3 Organic chemical analysis

Moisture Content determination

Throughout the testing procedures described in the following sections, moisture content of the sample was measured and accounted for. The reported values are always based on an oven-dry basis, where moisture content is equal to 0%, in order to ensure consistency in results.

Moisture content was measured following the oven-dry method. A representative sample from every population was weighed and placed in the oven at 103^0C ($\pm 2^0C$) for a period of 48 hours. Upon removal from the oven, the sample was immediately placed in a desiccator, where it could cool without reabsorbing moisture. After cooling, the sample was weighed again. The calculation used for moisture content is shown in Equation 3.1, and is taken from TAPPI Standard T 412 om-94 (TAPPI 1996) and PAPTAC Standard G.3 (PAPTAC 1998).

Equation 3.1 $$\%MC = (M_w - M_{od}) / M_{od} \cdot 100$$

where
M_w = wet mass of the sample (g)
M_{od} = oven-dry mass of the sample (g)
%MC = overall moisture content (%)

Note that the final moisture content is always reported as a fraction of the oven-dry weight of the specimen.

Extractive determination

The testing methods used to determine extractive content are outlined in TAPPI Standard T 264 om-88 (TAPPI 1996), as well as in PAPTAC Combined Standards G.13 and G.20 (PAPTAC 1998). Three extraction stages were employed to remove the full range of extraneous substances from the material, leaving behind the three major wood polymers contained within the sludge matrix.

The solvent systems utilized in the extractions have been honed over a number of years to remove the widest variety of extraneous material possible. The first extraction is carried out with a 1:2 mixture of 95% ethanol and analytical grade toluene. As a non-polar solvent, this mixture is effective at removing substances from the sludge that include waxes, fats, resins, salts, wood gums, phytosterols, and non-volatile hydrocarbons. The second extraction utilizes 95% ethanol, and serves as a rinse, removing any of these materials that the first cycle left behind. The third extraction uses pure distilled water, and removes tannins, gums, sugars, and colouring matter that are found in the material. This stage is effective at removing polar substances that are unaffected by the ethanol or ethanol-toluene solvent treatments.

Extractive content is calculated using Equation 3.2.

Equation 3.2 $$\%EC = (A - B) / S_{od} \cdot 100$$

where
A = oven-dried mass of extracted material (g)
B = oven-dry mass of the blank determination (g)
S_{od} = oven-dry weight of the sludge sample (g)
%EC = overall extractive content (%)

The blank determination referenced in the equation is obtained by running 5 samples composed only of string and Kimwipe, a cellulose tissue product. Blank runs were conducted to determine if any extractives were associated with these materials. These materials were then used to wrap individual sludge samples for the extraction procedures. The sludge material subjected to this procedure, having been rigorously cleaned with solvents and water, should now be composed only of the three major wood polymers as well as the other components of the sludge matrix. Therefore, these samples are used to determine the percentage that each of these polymers composes of the total sludge mass.

Holocellulose determination

As described in Chapter 2, holocellulose is the cellulosic portion of woody materials, containing alpha-, beta-, and gammacellulose. Together, beta- and gammacellulose are commonly known as hemicellulose. Testing of holocellulose was carried out following the method first pioneered by Zobel and McElwee (1966). This method involves treating the samples with an acid chlorite medium, which decomposes the lignin and allows the cellulosic material to be filtered out. Due to the intrinsic nature of wood, however, perfect separation of these polymers is not possible. It is accepted that some lignin will remain in the matrix, and that some holocellulose will be precipitated out after the acidic treatment (Lewin and Goldstein 1991, Zobel and McElwee 1966). As this method is not a standard test, a brief outline of the procedure is provided.

To conduct the holocellulose determination, 0.70 g of the extractive-free sample was weighed out and placed in a tared Erlenmeyer flask. 10 ml of an acid solution (60 ml glacial acetic acid and 20 g NaOH per liter of distilled water) was added to each flask. 1 ml of a chlorite solution

(200 g $NaClO_2$) was quickly stirred into each sample, and the flasks were placed in a hot-water bath regulated to 70^0C. Subsequent 1 ml chlorite additions were made after 45, 90, and 150 minutes. The flasks were left in the water bath for 4 hours in total, after which time the samples were removed from the water bath, and the contents of each flask drained into an oven-dried, tared coarse crucible. The liquid portion was removed under suction on a filter flask, and the solids were then washed with 100 ml of 1% acetic acid. A final rinse with acetone was carried out to ensure complete removal of moisture. The crucibles containing the samples were then placed in a conditioning chamber and allowed to equilibrate for 4 days, which brought the final moisture content of the material down to minimal amounts. The final step in holocellulose determination involved weighing the crucible and reporting the mass of holocellulose as a percentage of extractive-free sludge.

Alphacellulose determination

The alphacellulose fraction is determined by further reducing the holocellulose fraction of the sludge. Hemicelluloses are susceptible to the application of basic solutions such as sodium hydroxide, which degrade the bonds in cellulose and hemicellulose polymers and allow the smaller structures belonging to the hemicellulose group to be filtered out of the total mass. Because of the nature of the experiment, timing is very important. These methods are based upon the pioneering work done by Zobel and McElwee (1966); a brief synopsis of the methodology is provided.

The crucible containing holocellulose is placed in a watch glass filled with water to a depth of 1 cm. The reaction begins when 3 ml of 17.5% NaOH is added to the contents of the crucible. A glass rod is used to macerate the material and thoroughly combine the fibres with the sodium hydroxide. After five minutes, an additional 3 ml of 17.5% NaOH is added to the crucible to maintain the reaction. The crucibles are then allowed to stand for 35 minutes, after which the crucibles are placed on a filter flask and rinsed with 60 ml of distilled water under suction. The suction is then released, 5 ml of 10% acetic acid is added, and crucibles are allowed to drain by gravity for five minutes. The acetic acid serves to clean the frits of the crucible and thus allow the remaining hemicelluloses to be rinsed out of the mix. After reconnecting suction, the crucibles are rinsed with an additional 60 ml of distilled water. Finally, two 5 ml portions of acetone are rinsed through the alphacellulose to remove any trace of moisture. The crucibles are then oven-dried for 48 hours, and weighed. The mass of alphacellulose can then be calculated and reported as a percentage of extractive-free wood.

In order to determine the hemicellulose content of the sludge, the difference between holocellulose and alphacellulose measured in each sample is taken.

Klason Lignin determination

The techniques available for measuring lignin vary greatly, but the most widely accepted is the one that was originally pioneered by Klason and Hagglund (Lewin and Goldstein 1991). This method uses an acidic digestion to remove the polysaccharides in wood, and follows the assumption that lignin does not degrade to any great degree in acidic mediums. This method has been codified in TAPPI Standard T 222 om-88 (TAPPI 1996), as well as in PAPTAC Standard G.9 (PAPTAC 1998). It should be noted that while the insoluble lignin portion is by far the greatest, there is always slight dissolution of lignin in the method. Following the standard procedures, the cellulosic in the extractive-free sample was removed using a sulfuric acid wash under heat. The amount of acid-insoluble lignin is reported as a percentage of extractive-free wood mass.

Soluble Lignin determination

Soluble lignin is the portion of the polymer that is dissolved in acid during the determination of Klason lignin content. The method was first described by Johnson et al. in 1961, and was for a time listed as TAPPI Useful Method 250 (TAPPI 1990, Johnson et al. 1961). Normally, the dissolved fraction of lignin is very small, in the range of 1% for most softwood species, and as such is often ignored. Given the variable nature of the sludge being analyzed in this study, however, it was felt that all avenues should be explored.

The concentration of soluble lignin can be measured through the use of ultraviolet spectophotometry. The filtrate collected in the previous subsection was placed in a cuvette and measured for absorbance in the spectrophotometer, using a 10 mm light path at an ultraviolet wavelength of 205 nm. This wavelength and path are chosen to match the characteristic peaks of soluble lignin, and have been found to demonstrate sensitivity for variations in lignin concentration (White 1965). A standard solution of 3% sulfuric acid was used as a blank for this procedure allowing the spectrophotometer to dismiss the variation caused by the presence of acid in the filtrate.

The calculation for % soluble lignin content shown in Equation 3.3, which is taken straight from the TAPPI Useful Method.

Equation 3.3 $$\%SL = (A \cdot V \cdot F) / M \cdot 1100$$

where
A = absorbency of the filtrate (nm)
V = total volume of the filtrate (mL)
F = dilution ratio (V_d/V_o, where V_d = diluted volume and V_o = original volume)
M = oven-dry mass of the sample (g)
%SL = Soluble lignin as a percentage of extractive-free material

3.3.4 Inorganic chemical analysis

Ash content of sludge was determined by igniting samples at 525^{0}C for four hours. This procedure follows TAPPI Standard T 211 om-93 (TAPPI 1996) and PAPTAC Standard G.10 (PAPTAC 1998). The material remaining after incineration is completely inorganic, as all carbon complexes within the sample are combusted. Note that combustion also removes the plastic polymers, which are not composed of carbohydrates but which contain carbon that is ignited in the presence of oxygen.

A further reduction of the ash produced in the first part of the procedure can be carried out through acid hydrolysis. This method follows TAPPI Standard T 244 om-93 (TAPPI 1996) and PAPTAC Proposed Method G.33P (PAPTAC 1998). The ash is repeatedly dissolved in HCl, and then the resulting material is dried at 575^{0}C for four hours. The remaining material after the hydrolysis and subsequent incineration is primarily silica and silicates, and is treated as such for the purpose of this experiment.

3.4 Results and Discussion

3.4.1 Wood Component Identification

The results of the wood fibre identification tests are shown in Table 3.4. The data show strong variability in the fractions of detritus, cellulosic and lignosic materials.

In analyzing the data, several assumptions were made. The first assumption is that the crystalline fraction of material revealed under polarized light correlates to the holocellulose content of the sludge stream. It is acknowledged that the truly polarized area will only correspond to crystalline cellulosic material; however, in practice, the amount of area recorded by the computer included dim areas around the edges of the bright crystalline zones. This in effect biases the results to correspond more closely to the holocellulose, or total cellulose content. In each photograph examined, the only regions that glowed under polarized light were found on fibrous material, which corresponds to this assumption and precludes the possibility of other crystalline material being included in the sludge matrices.

A second assumption is that the material stained red with Analine Safranin is completely woody in origin, and that no woody material remained unstained on the slides. Visual examination of the slides could not verify or refute this assumption, but it is prudent to note that other, nonwoody organic material does respond to this stain and may have been included in the total area figures generated. An examination of the photomicrograph in Figure 3.3 (page 57) reveals several ambiguous areas that may or may not be woody in origin but do exhibit a red colouration. There was no way to differentiate this using the proposed test methodology, however, and no inferences were made at this point.

In Table 3.4 below, the total area revealed under polarized light has been subtracted from the total area stained with Analine Safranin in order to reveal the difference in areas. The third assumption here, therefore, is that the difference between these two areas represents the lignin fraction of the woody organic material suspended in the sludge.

Table 3.4 Results of wood fibre identification

		Mill A	Mill B	Mill C	Mill D	Mill E	Mill F
Detritus (Organic & Inorganic)	*Average:*	**31.6%[a]**	**34.1%[a]**	**35.5%[b]**	**36.8%[b]**	**42.2%[c]**	**47.5%[d]**
	Standard Deviation:	2.4%	1.8%	2.8%	2.3%	1.4%	1.1%
Crystalline Cellulosic Material	*Average:*	**58.1%[a]**	**56.8%[a]**	**47.1%[b]**	**47.2%[b]**	**38.4%[c]**	**33.1%[d]**
	Standard Deviation:	4.6%	4.9%	4.0%	1.3%	2.4%	2.5%
Lignosic Material	*Average:*	**10.3%[a]**	**9.1%[a]**	**17.4%[b]**	**16.0%[b]**	**19.4%[c]**	**19.4%[c]**
	Standard Deviation:	1.3%	1.0%	2.3%	2.1%	3.0%	2.7%

Sample means followed by the same letter (a,b,c) on the same row are not significantly different at $\alpha = 0.05$.

It can be seen from the table above that the cellulose component is highest in the virgin fibre mills (A and B), as might be expected. In these mills, the least amount of degradation has taken place and the fibres used are still in optimum condition, which would influence the amounts of cellulose present in any waste material. At the other four mills, the amount of crystalline cellulosic material found was lower, which may reflect upon the degradation that recycled fibres undergo.

In analyzing the macro characteristics of the sludge, it is useful to compare the data to the general parameters of the mill in question. It can be hypothesized that mill furnish and the processes used in the installation each play a role in determining sludge characteristics.

The furnish used in Mill A and Mill B are similar, as both mills use virgin fibre with a mixture of softwood (generally black spruce) and hardwood (various species, but typically poplar). Mill B does utilize a wider variety of hardwoods for different pulps, including maple and birch. The macro characteristics of the sludges from these two mills do not exhibit significant variation.

The recycling operations at Mills C, D, E and F use completely different sources of wastepaper as furnish. Mill C relies upon pre-consumer recovered waste with some virgin fibre and post-consumer waste added to the process as available. In comparison, Mills D, E, and F that rely almost completely upon post-consumer waste of different grades, with Mill D using mainly cardboard and linerboard waste, and Mills E and F utilizing old newspaper and magazines with some virgin fibre. Of these four mills, the sludges from Mills C and D exhibit mean characteristics that are not significantly different at low p-values. Mills E and F are significantly different, both from each other and from the other recycling operations, in two of the three categories measured. Thus, the two mills that use similar furnishes to create similar products (E and F) produce sludge with significantly different macro characteristics, and the two mills with different furnish, statistically similar sludges.

There does not seem to be a relationship between the mill process used and the macro characteristics of sludge. For instance, Mill A is a chemical pulping plant that uses the Kraft process, while Mill B is primarily manufacturing thermo-mechanical pulp. These processes are completely different, and yet the sludge characteristics found using the sampling technique are very similar, and statistically show no difference at $p<0.001$. Treatment processes at the two mills also differ; Mill A uses an aerated sludge basin (ASB), while Mill B uses an activated sludge (AS) treatment. The amount of detritus found at each mill is not significantly different, although the bacterial compounds used in each of the treatments varies based on the treatment type utilized. Mill C and D also utilize different processes to recycle fibres; different numbers of screens, washers and clarifiers are used. Finally, Mills E and F are both modern mills that use very similar processes in recycling, deinking, and waste treatment. The macro characteristics of the sludge from these installations, however, are significantly different.

It is clear upon analysis that some differentiation may be made between mills using virgin fibres vs. recycled fibres as furnish. It may be hypothesized that furnish does play a role in determining the sludge characteristics in virgin fibre operations. In recycling operations, furnish seems to have little relationship to the macro characteristics of the material. The processes used do not seem to have an influence upon the macro characteristics of the sludges of either virgin or recycled paper mills.

3.4.2 Organic chemical composition

The tests carried out to determine organic chemical content were originally designed for use with solid wood or pulp specimens. Accordingly, assumptions were made when applying these tests to papermill sludge. The first assumption is that each test overestimated the proportions of the relevant chemical component. The digestive processes used to remove and separate woody organic components should not affect extraneous materials present in the sludge, such as clays and inorganic fillers. Thus, the presence of these materials will be recorded in the proportions of each chemical component. The second assumption is that the proportions of woody organic components recorded are biased to the same degree, as similar amounts of extraneous material should be present in each.

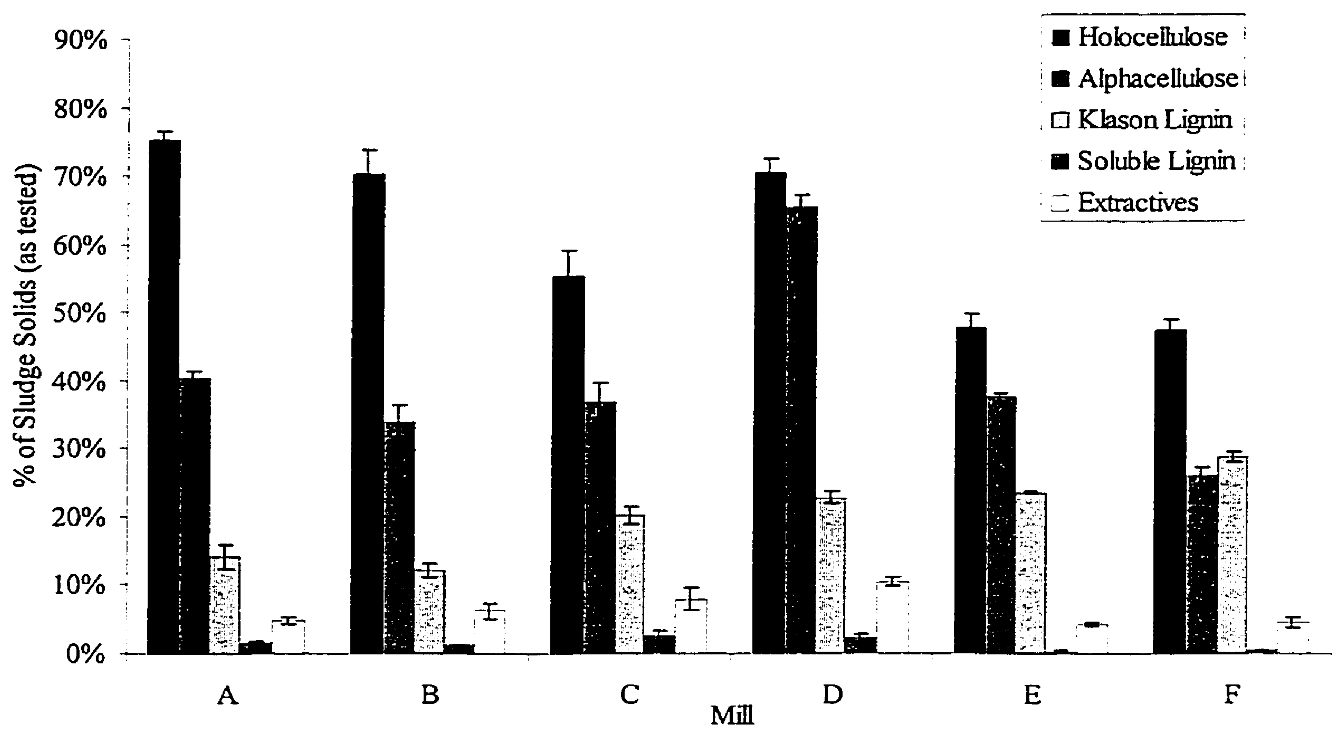


Figure 3.4 Average organic chemical composition of six papermill sludges

The results of the organic chemical testing are shown in Figure 3.4. The bars represent the mean primary data obtained during the experiment, while the error bars represent the standard deviation of each sample group. On the whole, the organic testing showed little variation within sample groups, an indication of the repeatability of this testing process.

Figure 3.4 illustrates several general trends. Holocellulose (comprising both alphacellulose and hemicellulose) is the dominant chemical group found in the sludges of all six mills. At the two virgin pulp mills, the relative amount of cellulose is higher than in the four recycled pulp mills. Lignin is found at lower levels in all mills, but at proportionally higher levels in the recycled paper installations. Finally, the amount of extractives seems to vary quite significantly from mill type to mill type, but is found at relatively small proportions in the sludges of Mills E and F.

An explanation for the reduction in cellulose and increase in lignin is can be found in the fact that most of the free cellulosic components in the form of broken fibres, shives, or fines, are removed during the formation of virgin paper. This leaves behind less woody cellular material that can be removed during recycling, and thus reduces the amounts of cellulose found within the waste stream. In response to this, the amount of lignin measured would increase. The presence of bark, or other materials that are present in virgin operations and not in recovered fibre operations, may also help explain the presence of additional cellulose within the sludge matrix for the virgin pulp mills.

The proportions of the various chemical components shown in Figure 3.4, while highly variable, are similar in four of the six mills tested. There are two exceptions, which both pertain to alphacellulose content. Mill D displays a much higher proportion of alphacellulose than the other five mills, with almost the entire holocellulose fraction consisting of pure alphacellulose. Conversely, Mill F is the only mill tested where alphacellulose is found at a lower concentration than Klason lignin. The methodology used in separating alphacellulose from the holocellulose matrix may account for some of the variability in the data regarding the pure cellulose fraction. The test was originally designed to analyze solid wood, not paper. The pulping process significantly changes the surface chemistry of wood fibres, which may affect the accuracy of the secondary hydrolysis utilized in this testing methodology (Section 3.3.3).

The statistical testing of the dataset was carried out using Duncan's test. The relative chemical components of the sludges from six mills were compared at a significance level of 0.05, as shown in Table 3.5.

Table 3.5 Results of Duncan's test comparing organic chemical components of six mill sludges

	Mill A	Mill B	Mill C	Mill D	Mill E	Mill F
Holocellulose	a	b	c	b	d	d
Alphacellulose	a	b	a	c	a	d
Klason Lignin	a	a	b	c	d	d
Soluble Lignin	a	a	b	b	c	c
Extractives	a	b	c	c	a	a

Mills with the same letter showed no statistically significant difference in mean component level at $p<0.05$.

Of the six mill sludges tested, only two showed statistically similar chemical compositions. Mill E and Mill F, both recycled paper plants using similar furnish and processes, have similar compositions in four of the five components tested, with the exception of alphacellulose. The variation between these installations and the other four mills considered would seem to indicate that the individual processes at each plant are driving the organic chemical characteristics of the sludge. Mills A and B, which use similar furnish but different processes, generate sludges with significantly different organic chemical characteristics.

It is useful at this point to address the assumptions made about the chemical testing procedures. By rearranging the data presented in Figure 3.4, the following illustration can be produced.

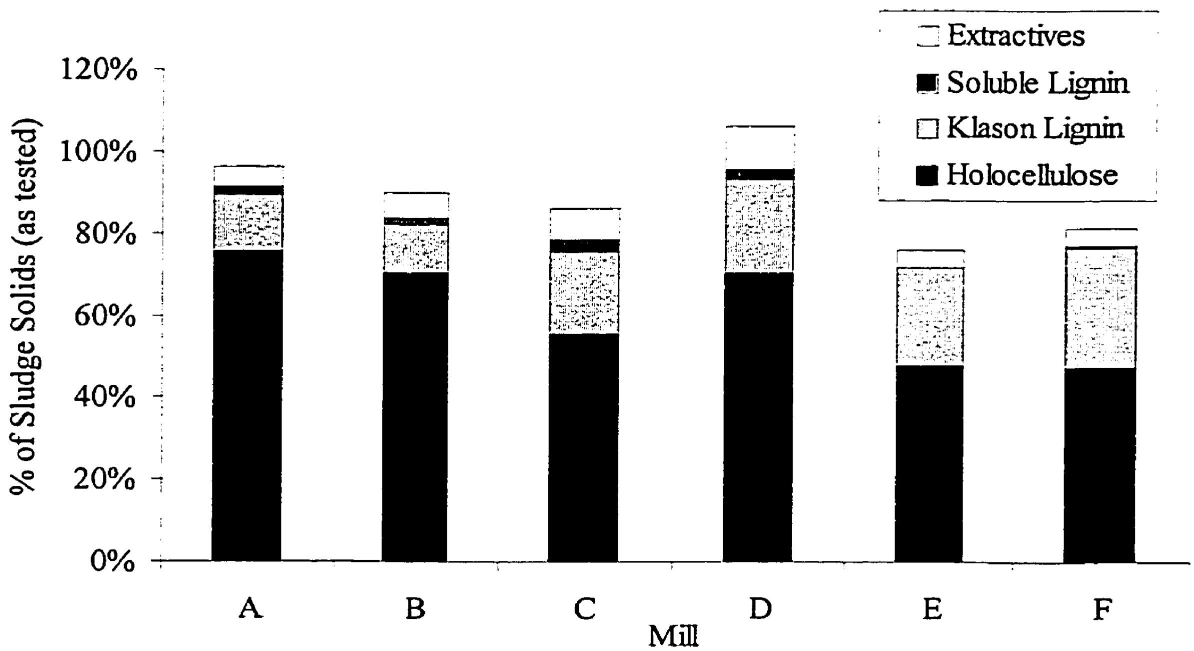


Figure 3.5 Proportional composition of cellulose, lignin, and extractives

From the graph above, it can be seen that in most cases the summed proportions of holocellulose, Klason and soluble lignin, and extractives do not exceed 100%. Only Mill D displayed a total in excess of 100%. While these results might be typical in the analysis of solid wood, in this case the sludge being analyzed contains known contaminants such as dead organic material and inorganic detritus, as shown by visual examination in the previous section. Thus, the assumption that each of these fractions is inflated to some degree is warranted. Testing was carried out to determine the amount of non-woody material that remains after cellulose digestions or lignin hydrolysis testing. Unfortunately, these tests were inconclusive, and were not able to determine a consistent ratio of woody organic vs. other materials. This may be due to the variable nature of the sludge.

The testing of organic chemical composition of six mill sludges showed no clear relationship toward furnish characteristics. There was some indication that sludges from virgin pulp mills have higher proportions of cellulosic material, and lower proportions of Klason lignin. The results for recycled paper installations, however, were not consistent and reflected the variability associated with both furnish quality and process parameters. It is surmised that process is a stronger controlling factor in determining the chemical composition of mixed papermill sludges.

3.4.3 Inorganic chemical composition

The inorganic components of sludge are shown in **Figure 3.6**. Unlike the organic determinations carried out in the previous section, the nature of testing used here provides a precise measurement of the inorganic material within the sludge.

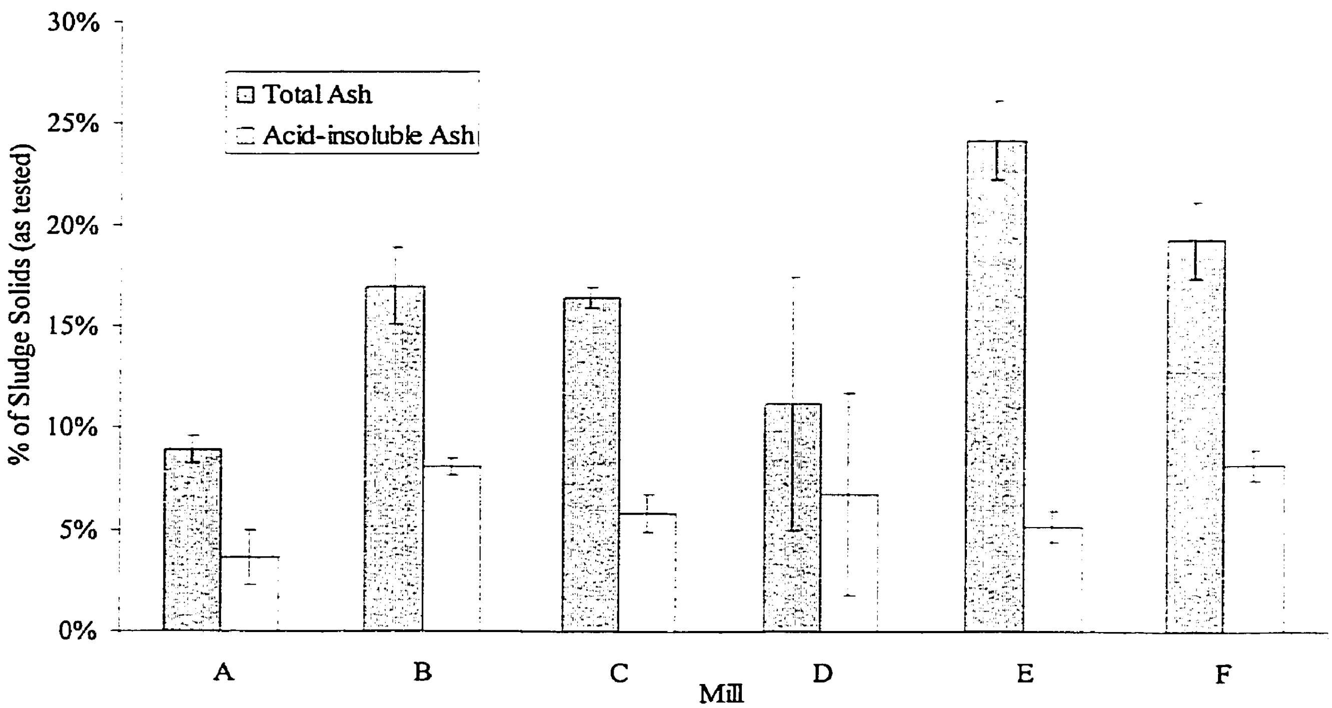


Figure 3.6 Inorganic composition of six papermill sludges

It is evident from this figure that soluble and insoluble ash contents are highly variable from mill to mill. The datasets of inorganic material observed had a great deal of inherent variability, as is shown by the high standard deviations associated with many of the mean observations. In particular, Mill D displayed a great deal of variability, which may reflect the lack of secondary treatment on the site of this installation. Of the six mills tested, Mill A had the smallest inorganic fraction. At the other five mills, the inorganic fraction was substantially higher, although the proportion of soluble and insoluble components varied significantly. Mill A uses the Kraft process to pulp softwood and hardwood chips, while the other installations use mechanical processes to pulp or recycle more variable fibre sources. The chemical pulping process may act as a cleaning process, removing much of the inorganic material from the wood fibres and thus removing inorganic material from the solid waste stream. This may indicate a relationship between mill process and the inorganic fraction present in sludge.

Upon further examination, the data also suggests a relationship between the furnish used and the amount of inorganic material present in the sludge. Mills E and F, which are both characterized by significantly high ash content, are both recovered paper plants dealing primarily in newsprint that utilize a deinking stage. Inorganic elements present in inks and paper surface treatments may account for the higher proportion of ash in this material. There was a great deal of variation between recycling installations, however, with no two installations standing out as being statistically similar. The results of statistical testing, where the inorganic content of mixed sludges were compared at a significance level of 0.05, are shown in Table 3.6

Table 3.6 Results of Duncan's test comparing six mill sludges

	Mill A	Mill B	Mill C	Mill D	Mill E	Mill F
Total Ash	a	b	b	c	d	e
Acid-insoluble Ash	a	b	b	c	c	b

Mills with the same letter showed no statistically significant difference in mean component level at $p<0.05$.

The statistical tests indicate that, of the six mills tested, Mills B and C have statistically similar inorganic content, while the other four mills are significantly different from both these mills and from each other. Mills B and C do not share common sources of fibre or interior mill processes, however, and thus the similarity indicated may in fact be coincidental. The data indicates that mill processes, rather than fibre source, is more likely to influence the inorganic composition of mixed papermill sludges.

3.4.4 Verification of testing methodology

In order to verify the identification of woody organic material, a comparison can be made between the preliminary results obtained through photomicrography and the data obtained through standard test methods.

In identifying woody organic material, quantities of holocellulose and lignin were determined on a visual basis. These figures can be compared to the absolute values of holocellulose, Klason and soluble lignin observed. As the absolute values already contain a significant proportion of non-woody organic and inorganic material, a straight comparison is impossible. The ratios of cellulose-to-lignin should be similar for both techniques, however, and these ratios are compared in Figure 3.7.

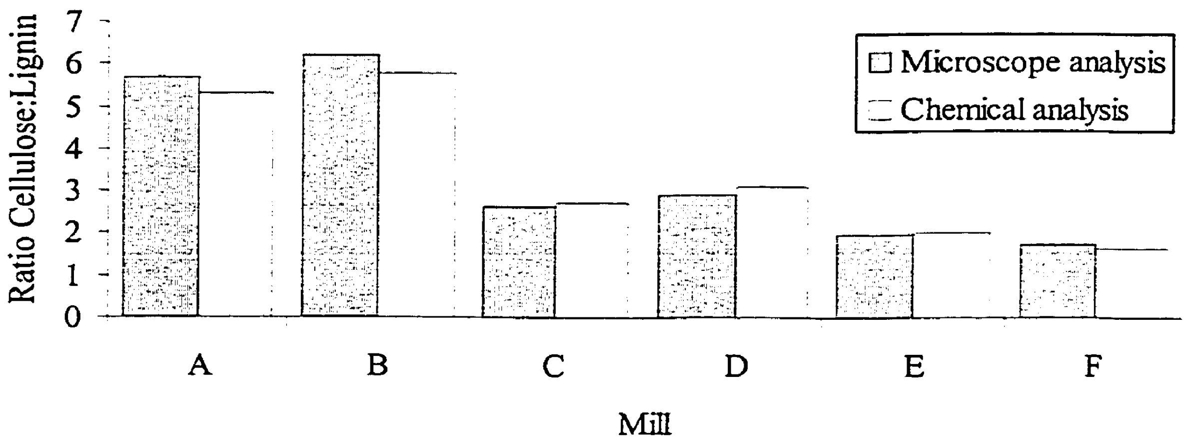


Figure 3.7 Cellulose:Lignin ratios, microscope and chemical analyses

At each of the six mills in question, there was no significant difference in the mean ratios of cellulosics to lignosics ($\alpha = 0.1$). The similarity between each test method lends support to the proposed methodology. The amount of inorganic material measured in each mixed sludge sample is an absolute figure that indicates the true size of the inorganic fraction. These data, as illustrated in **Figure 3.6**, are considerably lower than the measured amount of organic and inorganic detritus reported in Table 3.4. This fact also confirms that the proposed methodology for identifying wood components within the sludge matrix is valid.

3.5 Conclusions

The principal conclusions that can be drawn from this section of work are:

1. The proposed analysis technique for quantifying the presence of woody materials within the sludge matrix provides reasonable measurements of components that are not contradicted by more accepted methodologies of chemical determination. It can be deemed effective in the absence of a more precise tool for measurement.

2. The chemical nature of mixed papermill sludge is, on average, dominated by the presence of non-woody organic and inorganic material (>35%) and by alphacellulose (>25%). Components originating from wood fibres compose more than 60% of the total sludge solids on average.

3. The macro characteristics of papermill sludge do not show a relationship to papermaking process, but is related to the raw material used, particularly in virgin pulp mills.

4. The organic and inorganic chemistry of sludge is influenced more by pulping process than by raw material, and particularly by the presence or absence of recycling.

4 Effects of time and process on mixed sludge characteristics

4.1 Introduction

4.1.1 Abstract

As wood is processed and recycled, the amounts of fibre and fines within the effluent stream varies, both in physical characteristics and in chemical composition. In order to measure this variability, the six mills in the study were grouped into three mill categories, in order to describe sludge composition more specifically. The sludge output from 2 recycling mills was measured over extended periods to determine in-stream variability, and the average values and confidence intervals for several physical and chemical parameters of sludge have been described. It has been shown that alphacellulose is the most variable woody organic component found within sludge. The other woody components tend to be less variable, and it was shown that three mill categories describing sludge output could be established through an analysis of these components. The inorganic components of sludge were not found to correspond to the proposed groupings, however, and the physical characteristics of papermill sludges showed little variation between proposed mill categories.

4.1.2 Objectives

The overall goal of this chapter, as described in Chapter 1, is to assess the degree to which sludge chemistry varies over time, and how processes can affect sludge chemistry and woody carbon content. In order to do this, effluent material was collected from six mills representing three general mill types. Mean levels of wood chemical components and confidence intervals for each were determined.

The specific objectives of this study are to:

1. Quantify the variation in the woody organic portion of sludge over time, in terms of organic chemical components such as cellulose, hemicellulose, and lignin;
2. Compare the sludge composition of different mills, and group mills into categories based upon the chemical characteristics of the sludge;

3. Describe the unique chemical and physical properties of sludge from each mill grouping, and;
4. Express the sludge outputs of different mills in terms of woody carbon, in terms of average levels and inherent variation based upon the source.

4.2 Sample Collection

The analyses completed in this chapter are based upon the sample sets described in Chapter 3.

4.2.1 Criteria for mill selection

The selection of the mills sampled for this study was based upon several factors, including accessibility, location, product, and process, as described in Section 3.2.1. In addition to the two criteria set out in the aforementioned section, a third criterion was added as follows.

3. That, when sampling was carried out over sequential days, there was no deviation from the normal operation of the mill in the form of downtime, machine breaks or stock spills, from the initial sample point until the final sample point inclusively.

Inclusion of this criterion was important to control for possible changes in sludge characteristics due to process or furnish variation.

4.2.2 Mill locations and operational parameters

A complete description of mill locations, processes, treatment systems and products can be found in Section 3.2.2.

4.2.3 Sample collection, preparation, and storage

The samples were collected according to the methodology set out in Section 3.2.3. Samples were prepared for analysis as described in Section 3.2.4.

The total number of sample dates at each installation depended upon mill accessibility. Mill C was sampled 15 times over a five week period, while Mill D was sampled only 5 times over another five week period.

Mill E was sampled 5 times, but sampling at this installation was discontinuous and was carried out over several years. These samples do not meet the criteria established for sampling described in Section 4.2.1. The results are included here, however, as they shed light upon changes that sludge stream chemistry can display over the long term.

4.3 Methods

The identification of the woody organic components within the sludge matrix was carried out using the methodology described and tested in the previous chapter. Chemical testing methods used to identify are also found in Chapter 3, Sections 3.3.2 – 3.3.3.

Additional testing was carried out to measure fibre characteristics such as length, kink, and coarseness, in order to describe the physical properties of the woody component of sludge. The overall testing methodology followed the flowchart shown below.

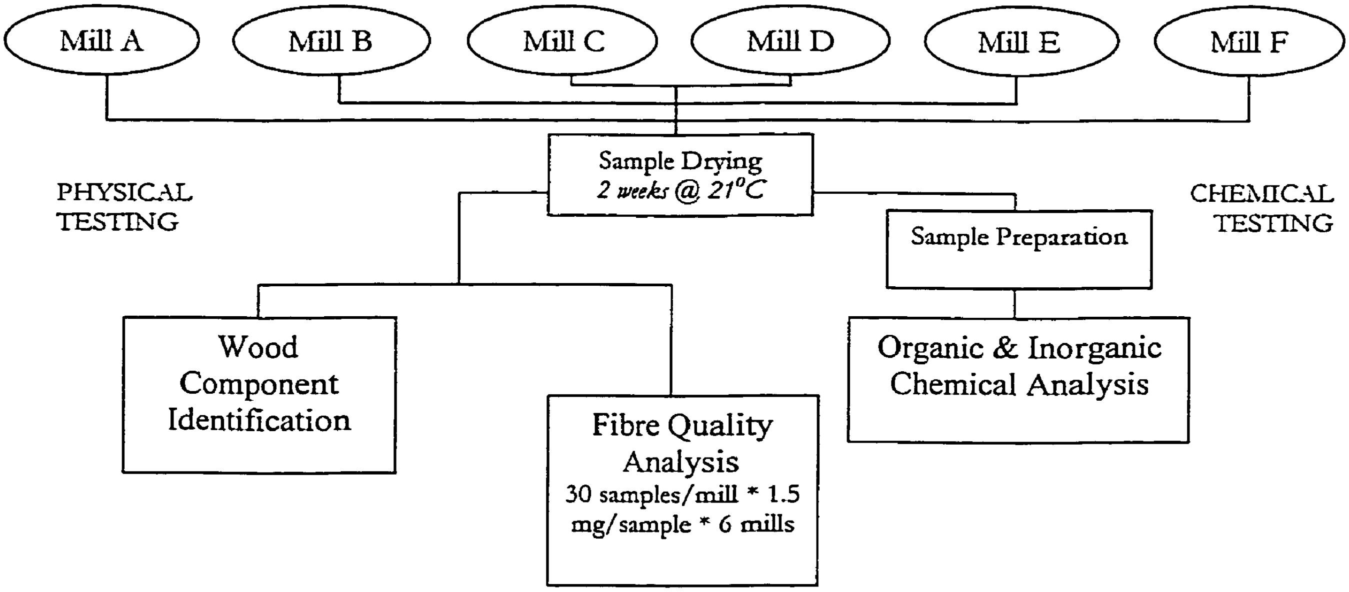


Figure 4.1 Modified flowchart of experimental design

4.3.1 Fibre quality analysis

In testing for physical properties such as fibre length, curl, kink and coarseness, analyses were carried out using an automated fibre analyzer commonly known as FQA testing apparatus. The operating manual for FQA by OpTest Equipment Inc. was followed

Fibre length was determined following the procedure outlined in PAPTAC Standard B.4P (PAPTAC 1998), which closely approximates TAPPI Provisional Standard T271 pm-91 (TAPPI

1996). A 5L pulp suspension was made with a consistency of 0.01% (± 0.002%). This suspension was then run through the FQA, which passes the suspension through a fibre-orienting cell (FOC) where the projected length of the individual fibres in the solution is measured. The calculation for fibre length is shown in Equation 4.1.

Equation 4.1

$$L_W = \frac{\sum_{i=1}^{N} n_i l_i^3}{\sum_{i=1}^{N} n_i l_i^2}$$

where
L_W = the length-weighted average length
n_i = the total number of measured fibres in category i
l_i = average length of category i
N = total number of categories

Because there was concern over the expected large fraction of fines, it was decided that analysis of the length would be done on a weight-weighted basis. By creating an average length based on the weight of the fibres, a more representative average can be created (PAPTAC 1998).

The frequency distribution of this data was created on length-weighted basis. The equation for this distribution is found in Equation 4.2.

Equation 4.2

$$P_{L,i} = 100 \cdot \frac{n_i l_i}{\sum_{j=1}^{N} n_j l_j}$$

where
$P_{L,i}$ = the percentage of length in category i
n_i = the total number of measured fibres in category i
l_i = average length of category i
N = total number of categories

The frequency distribution was created on a length-weighted basis in order to create a more balanced distribution of the results, for similar reasons as above.

Fibre coarseness was directly measured within the FQA analysis. It is defined as the oven-dried mass per unit length of fibre (Pande 1999), and is normally expressed in units of dg, which denotes mg of cell wall material per 100 metre of fibre. It is noted that the value of coarseness is greatly influenced by the accuracy of the mass measurement.

4.4 Results and Discussion

4.4.1 Sludge stream variations

When the chemical characteristics of the woody organic fraction of sludge are examined over an extended sample period, natural variations in the chemistry of the material become apparent. The analysis of sludge from Mill C indicates that this variation is actually quite small. The results of chemical testing are shown in Figure 4.2.

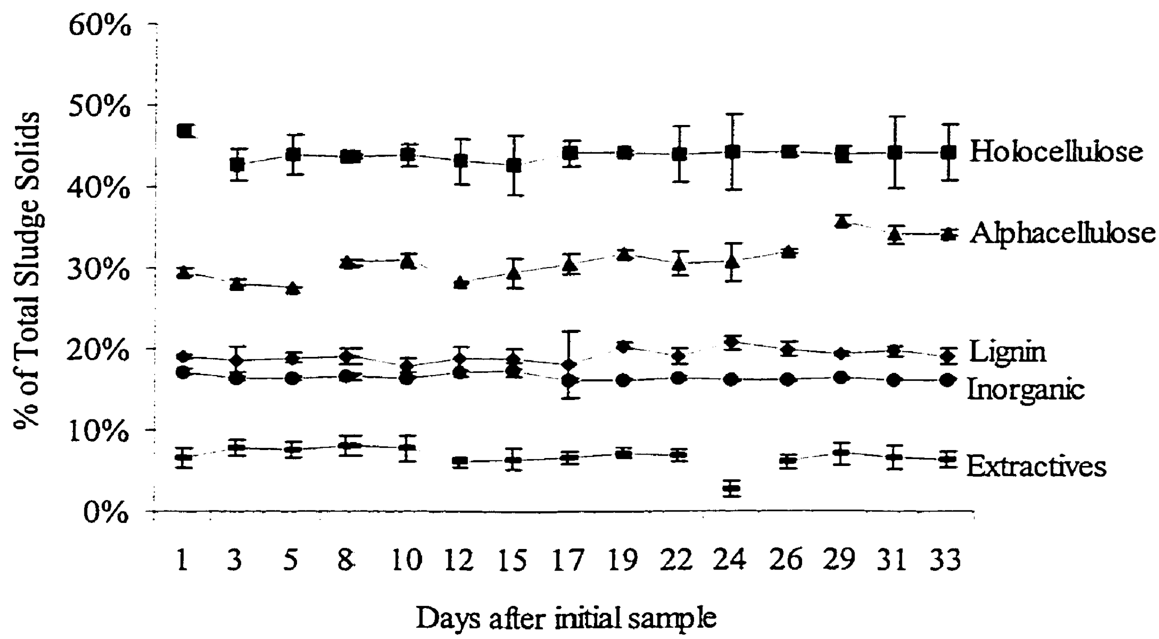


Figure 4.2 Variation in mean sludge chemistry (Mill C). Error bars indicate standard deviation

When subjected to ANOVA, it can be shown that the level of holocellulose, lignin and extractives each do not vary significantly over time ($\alpha = 0.05$). At this confidence level, alphacellulose does show significant variation within individual samples, as indicated by the large standard deviations associated with many of the sample dates. Alphacellulose is also the only component that is found at mean levels that differ by more than one standard deviation from the mean of the previous sample, on more than one occasion. While this is not a standard test, it is an indication of the real variance in this chemical group. Holocellulose, lignin, and extractive levels do not vary to the same extent.

The level of inorganic material in the sludge does not show any statistically significant variance over time (α = 0.05). At this particular mill, the papermaking process does not include deinking or recycling of a large amount of post-consumer waste, which would reduce the amount of inorganic contaminants that might enter the sludge stream.

Extended sampling undertaken at Mill D provided a different viewpoint. While the number of sample points was reduced, some of the same patterns in woody component variance can be seen, as shown in Figure 4.3.

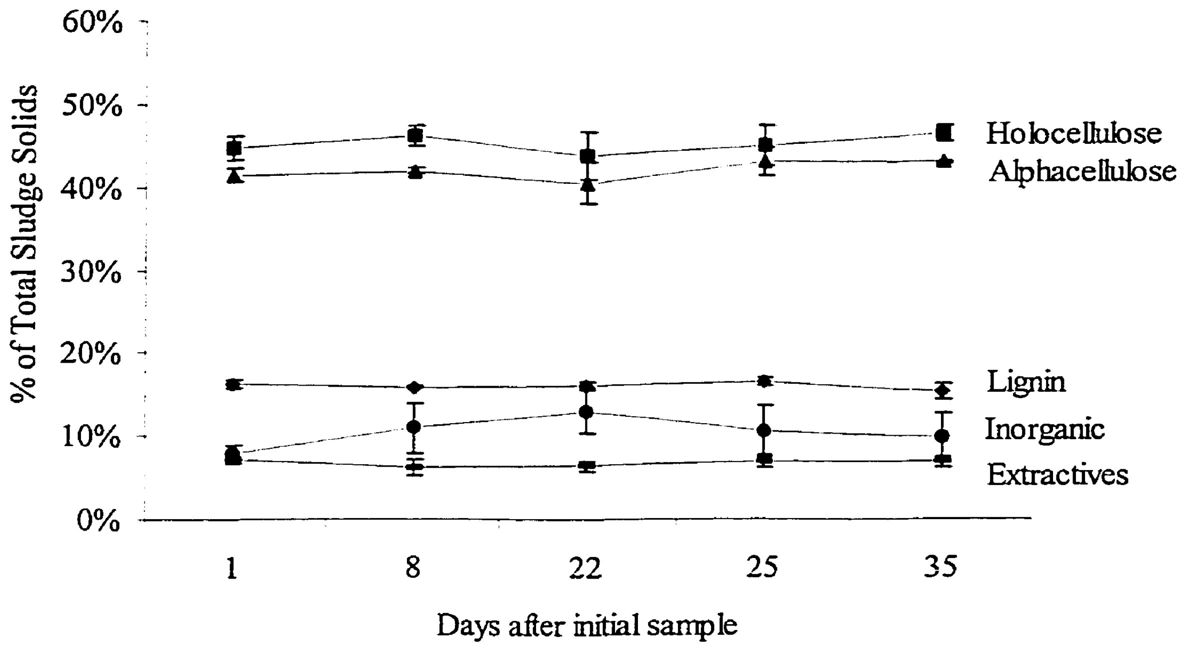


Figure 4.3 Summary of sludge variation (Mill D). Error bars indicate standard deviation

At this installation, none of the four wood chemical components measured showed significant variation (α = 0.05). This may be a reflection of the small sample size. Unlike Mill C, the mean level of holocellulose in Mill D sludge did not show extremely high standard deviation. Alphacellulose levels did not vary significantly, and also showed lower standard deviations than found in the samples taken at Mill C. There were no outlying data points in the results of this testing, which again can be attributed to the small sample size.

The levels of inorganic material found in this sludge did vary significantly, and showed very high standard deviations. This may be associated with the feedstock associated with the mill, which used post-consumer waste cardboard and paper. Post-consumer paper is often dirty and can be highly variable in nature, and the type of cardboard being recycled might differ from day to day. In addition, while the number of sample points is lower, the sampling period is significantly longer for Mill D than for Mill C. The quality and source of recovered post-consumer waste might change significantly in one or two-week increments.

Samples were taken from Mill E on five occasions, beginning in 1996 and ending in 1999. As stated in Section 4.2.3, this sampling regime did not meet the established criteria for sludge collection. Thus, there may have been changes to process, feedstock, and waste treatment practices in between one or more of these data points, and the mill may not have been in constant production. From the point of view of waste characteristics, however, these data provide a realistic picture of how sludge chemical characteristics may change over the long term. The results of chemical testing are shown in Figure 4.4.

Figure 4.4 Summary of sludge variation (Mill E). Dotted lines indicate non-consecutive samples

It can be seen from the graph above that the results of chemical testing are highly variable over the long term. The mean levels of each fraction displayed show significant variation ($\alpha = 0.1$). The actual variation in mean holocellulose levels is approximately 5% by mass of total sludge solids. The actual variation in alphacellulose levels is even higher, at approximately 13% by mass. The mean variations found in lignin and extractive levels are substantially lower, however. The mean inorganic fraction of this sludge varied by approximately 5%. These results indicate that long-term variation in sludge properties can be significant when production processes, feedstock, and operation are not held constant.

The data collected at Mills C, D, and E all indicate that alphacellulose levels vary the most in sludge composition over time. The variation associated with holocellulose, lignin, and extractives is lower and perhaps more predictable.

4.4.2 Provisional grouping of sludges by macro characteristics

In Chapter 3, the analysis of data indicated that the macro characteristics of sludge, in terms of detritus, cellulosics, and lignosics, do not show a strong relationship to the pulping processes employed. At the same time, the woody organic and inorganic chemistry of sludge seemed more influenced by process, and less by the raw material employed.

The macro characteristics of sludge were first presented in Table 3.2. In Table 4.1 below, the significant differences in sludge characteristics are indicated by the use of different letters. The mill attributes are listed below for comparison.

Table 4.1 Macro characteristics of sludge and corresponding mill attributes

	Mill A	Mill B	Mill C	Mill D	Mill E	Mill F
Organic/Inorganic						
Detritus:	a	a	b	b	c	d
Crystalline Cellulose:	a	a	b	b	c	d
Lignin:	a	a	b	b	c	c
Mill Type:	Kraft	TMP/ Sulphite	Recycling	Recycling	Recycling	Recycling
Flotation Deinking:	No	No	No	No	Yes	Yes
Fibre Source:	Virgin	Virgin	Pre-consumer	Post-consumer	Post-consumer	Post-consumer
Secondary Treatment:	ASB	AS	AS	–	AS	AS

Of the six mills indicated in the table above, three distinct categories of sludge characterized by similar compositions can be discerned. Category I includes Mills A and B. These installations both pulp virgin fibre, although they utilize different processes. The treatment of effluent streams is also different at these installations, with Mill A using a lagoon system and Mill B employing an activated sludge system. Despite these differences, the macro characteristics of the sludges generated at these mills are very similar. The inference that may be made here is that virgin pulp mills, each employing efficient yet different pulping processes and effluent treatment systems, will produce sludges that have similar solid compositions.

Categories II and III both apply to recycling installations. Category II encompasses Mills C and D. The feedstock used at these mills is different, as are the processes employed and the end product; Mill C is a fine paper plant while Mill D is a dual line linerboard plant. Neither Mills C nor D employ advanced deinking operations, however, and neither use large quantities of post-consumer magazines or newsprint. Both mills, however, recycle pre- and post-consumer waste without a deinking stage.

Mills E and F are assigned to Category III. Both mills produce recycled newsprint, and both use advanced flotation deinking cells within their process. The macro characteristics of Mills E and F are not completely similar, and yet are more similar to each other than to any of the other mills.

4.4.3 Corroboration of Mill Category assignments

Comparison of organic chemical composition

The three mill categories tentatively assigned in Section 4.4.2 are based solely upon the macro characteristics of the solid portion of sludge. In order to validate these assignments, a careful examination of the chemistry of this material must be undertaken.

Using data originally presented in Table 3.2, Figure 3.5, and Figure 3.6, the total composition of sludge solids from each of the six mills can be estimated, and is shown in the figure below. The combined value of organic and inorganic detritus corresponds with the total amount of detritus reported in Table 3.2. The proportion of inorganics reflects the absolute amount of ash measured in the sludge solids. The proportions of woody organic chemicals in the figure below correspond to the proportions of chemicals shown in Figure 3.5, but have been scaled to reflect the fraction of organic material shown in Table 3.2. The transformation of data was necessary to reflect the true proportions of cellulosic and lignosics material present in the sludge solids. The total amount of sludge solids was assumed to be 100% of the solid mass.

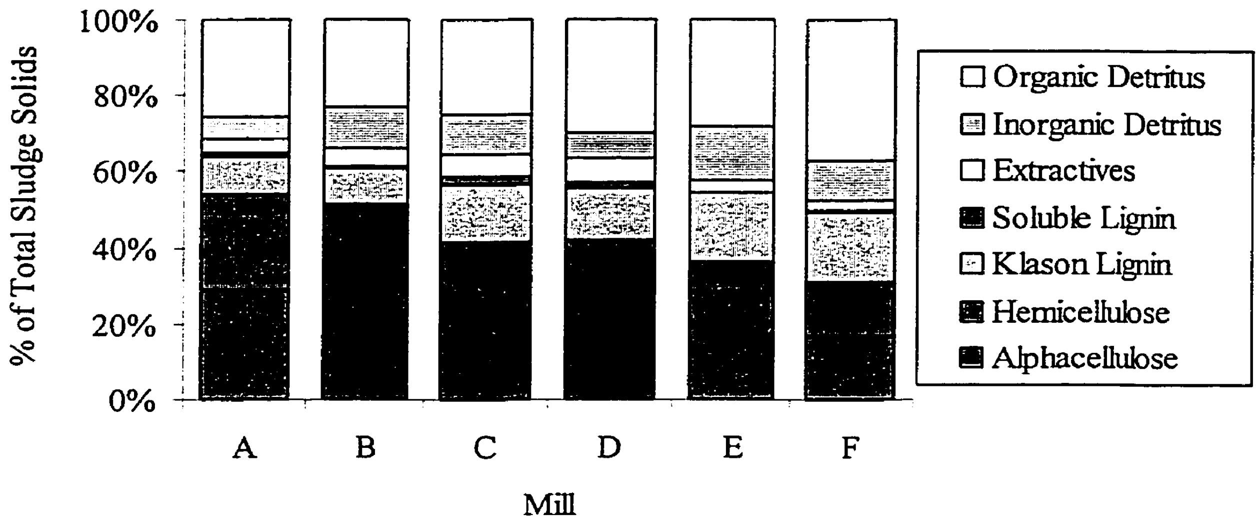


Figure 4.5 Proportional levels of chemical components of sludge

It can be seen from the figure above that there is significant variation in the levels of various wood components between mills. In particular, the reported levels of alphacellulose and hemicellulose show no distinct pattern and do not seem to bear any relationship to the category assignments applied in the previous section.

Table 4.2 describes the proportional amounts of wood chemical components independently, in order to illustrate the variation found within this fraction of the sludge.

Table 4.2 Organic chemical components of the woody fraction of sludge

Location	Holocellulose	Alphacellulose	Hemicellulose[Ψ]	Klason Lignin	Soluble Lignin	Extractives
All Mills						
Mean	66.4 %	43.8 %	22.6 %	22.7 %	2.0 %	8.9 %
Standard Deviation	10.0 %	10.9%	n/a	4.6 %	1.0 %	2.2 %
95% Confidence Int.	2.0 %	2.4 %	n/a	0.9 %	0.2 %	0.3 %
Mill A						
Mean	78.5 %	42.1 %	36.5 %	14.8 %	1.7 %	5.0 %
Standard Deviation	1.2 %	1.1 %	n/a	1.7 %	0.1 %	0.6 %
Mill B						
Mean	78.2 %	37.8 %	40.4 %	13.6 %	1.3 %	6.9 %
Standard Deviation	3.5 %	2.4 %	n/a	1.0 %	0.1 %	1.1 %
Mill C						
Mean	64.2 %	43.0 %	21.3 %	23.6 %	3.0 %	9.2 %
Standard Deviation	3.8 %	2.7 %	n/a	1.3 %	0.8 %	1.7 %
Mill D						
Mean	66.6 %	61.9 %	4.7 %	21.5 %	2.1 %	9.8 %
Standard Deviation	2.2 %	1.9 %	n/a	0.9 %	0.7 %	0.7 %
Mill E						
Mean	62.9 %	49.3 %	13.7 %	31.0 %	0.4 %	5.7 %
Standard Deviation	2.0 %	0.6 %	n/a	0.1 %	0.2 %	0.3 %
Mill F						
Mean	58.4 %	31.9 %	26.4 %	35.5 %	0.5 %	5.7 %
Standard Deviation	1.6 %	1.4 %	n/a	0.7 %	0.1 %	0.8 %

*Corrected to 100% of ash-free, woody organic component
[Ψ]Calculated as Holocellulose – Alphacellulose

The data shown in the table above quantifies the amount of variation associated with holocellulose, alphacellulose and hemicellulose within the sludge matrix. As alphacellulose is determined through a secondary hydrolysis of the material derived through holocellulose testing, it is not surprising that the variation shown by both components should be within the same range. The relative mean values that are shown in the table, however, indicate that alphacellulose is a much more variable component than holocellulose. This is supported by the wide confidence interval associated with alphacellulose.

Based upon these observations, and upon the observations found in Section 4.4.1, it can be postulated that the alphacellulose component is too variable to base conclusions upon. By ignoring the alphacellulose levels in individual mills, and considering the other wood chemical components as an independent group, Figure 4.6 can be constructed.

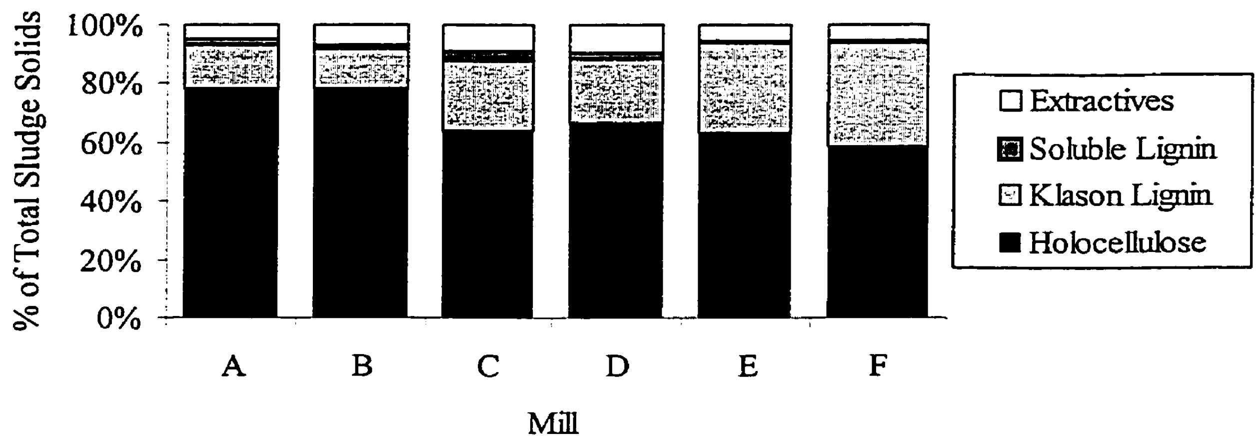


Figure 4.6 Mean chemical components of the woody fraction of sludge, considered independently

In this figure, each woody organic component present in the sludge is expressed as a fraction of the total amount of woody organic material. The three tentative groupings of A & B, C & D, and E & F are clearly delineated by the resulting data. The first category, grouping sludges from Mills A & B, exhibits a significantly higher relative proportion of holocellulose than the other two groupings, and the levels of all wood chemicals found at the two mills are very similar. The second category, including Mills C & D, exhibits a higher relative proportion of lignin and extractives than the first category, and the two mills once again show similar wood chemical characteristics. Finally, the third category of mill has the highest relative proportion of lignin and the lowest relative proportions of holocellulose. As this comparison is of relative values only, it is impossible to conduct any statistical tests of significance upon the dataset. The figure does support the initial category assignments, however, and illustrates the relative wood chemical components of each category effectively.

Analysis of data distributions

A technique that may be used to verify the category assignments is to review the distribution of observations of the wood chemical components in the three provisional categories under consideration. If the datasets display a normal distribution, it will add a degree of statistical confirmation to the validity of the category assignments.

It is important to note that the distributions provided are based upon the actual measured values, and that these data have not been transformed in any way. The use of transformed data for this portion of the analysis would influence the distribution curves and lead to false conclusions. In the previous subsection, the relative proportions of holocellulose, lignin, and extractives were examined in order to facilitate comparison.

The frequency distributions of holocellulose observations for each category are shown in Figure 4.7.

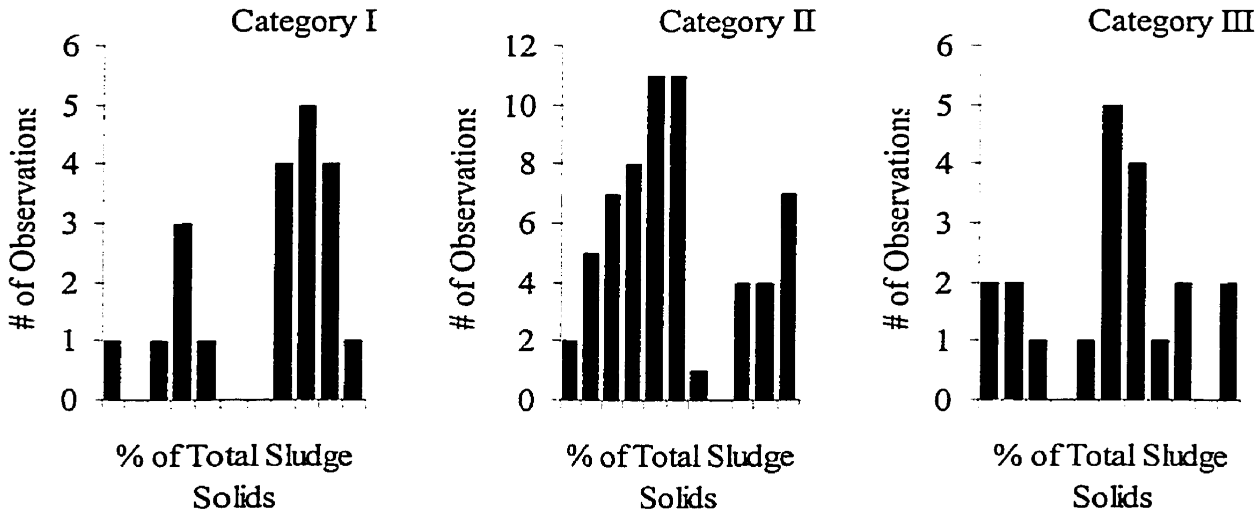


Figure 4.7 Histogram of Holocellulose observations

The first thing that is immediately obvious from the figure above is that the size of the datasets is not optimal. Serious gaps exist in the data available, and this influences the degree to which observations can be made. The kurtosis of each distribution was measured and is presented in Table 4.3.

Table 4.3 Factors describing the distribution of holocellulose observations

	All Mills	Category I	Category II	Category III
Standard Deviation (σ^2)	10.0 %	7.5 %	3.7 %	1.8 %
95% Confidence Interval	1.96 %	1.89 %	1.61 %	.077 %
Kurtosis	–	0.0032	0.198	1.325

The measure of kurtosis indicates the peakedness of the distribution, or the degree to which the curve follows the normal distribution. In each case here, the kurtosis is positive, and in two out of three cases the number is quite close to zero, which indicates that the curve lies relatively close to the normal distribution. The small data set used may contribute to the peakedness of the third sample, which more closely resembles a t-distribution in shape.

The Klason lignin test was more repeatable than the test for holocellulose, and this is reflected in the distributions shown. Each of the three provisional mill groupings displayed observations that most closely resembled a t-distribution. This reflects the small sample size, and the presence of gaps in the observed values. The distribution of Klason lignin observations is shown in Figure 4.8.

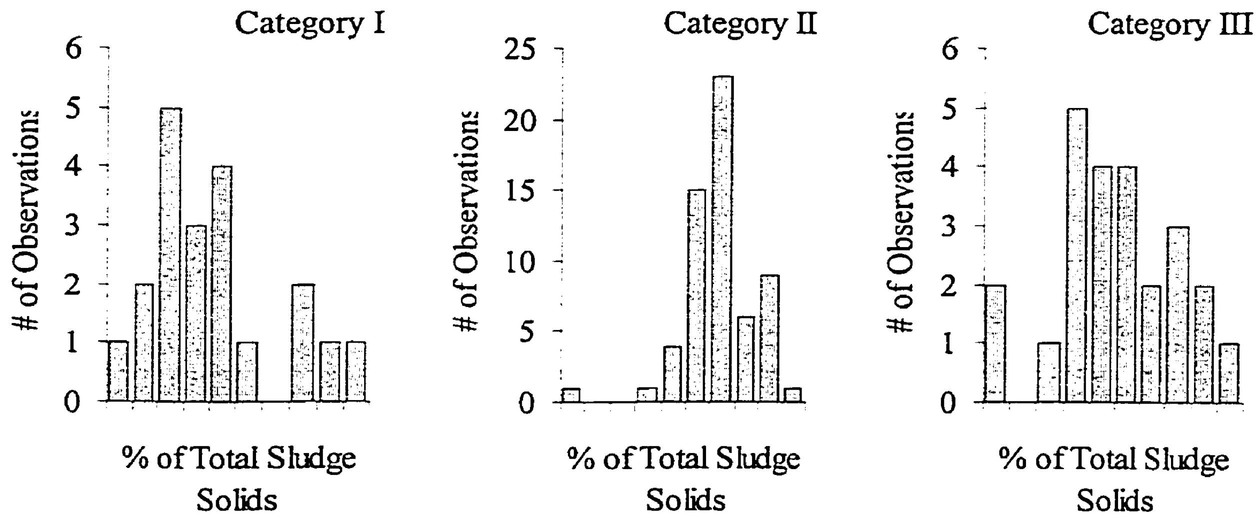


Figure 4.8 Histogram of Klason lignin observations

The distributions of Klason lignin demonstrate strong peakedness, which indicates that each provisional grouping is characterized by a range of Klason lignin concentrations that center on a common value. The test for soluble lignin provided similar results, as shown in Figure 4.9.

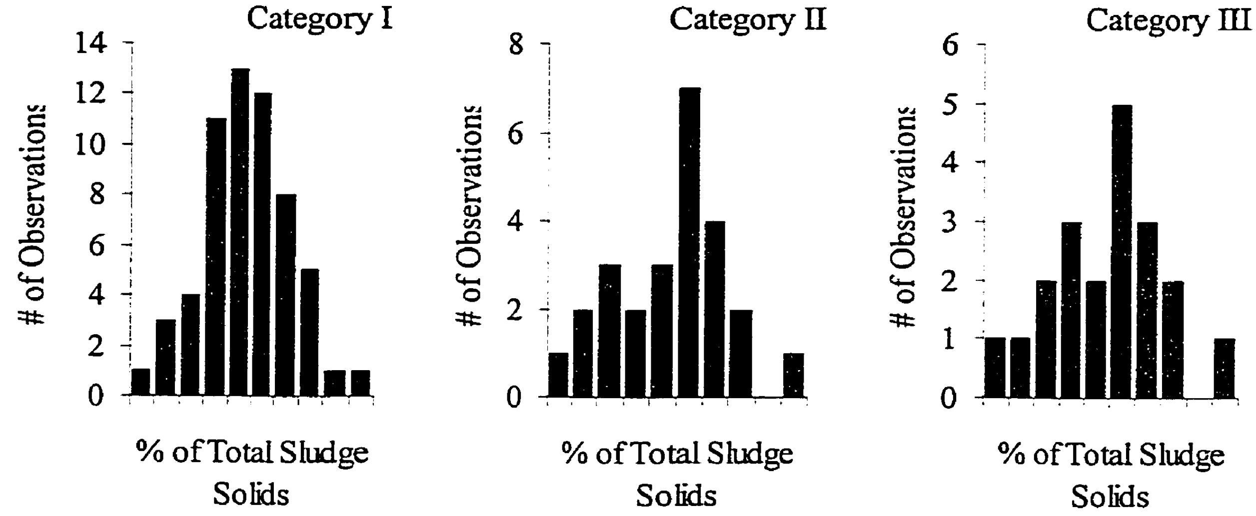


Figure 4.9 Histogram of soluble lignin observations

In the case of Klason lignin, the observations were strongly peaked, as indicated by the high kurtosis values, and the very low standard deviations and confidence intervals associated with each category of sludge, as shown in Table 4.4. Soluble lignin values, shown in the same chart, tended to be closer to flat values. The standard deviation and confidence intervals indicated for soluble lignin indicate that the actual range of values was very high, in proportion to the low values typically observed for this component.

Table 4.4 Factors describing the distribution of Klason and soluble lignin observations

	All Mills	Category I	Category II	Category III
Klason lignin:				
Standard Deviation (σ^2)	4.6 %	1.6 %	1.7 %	2.7 %
95% Confidence Interval	0.90 %	0.41 %	0.76 %	1.20 %
Kurtosis	–	1.436	2.292	1.090
Soluble lignin:				
Standard Deviation (σ^2)	1.0 %	0.8 %	0.2 %	0.5 %
95% Confidence Interval	0.20 %	0.20 %	0.10 %	0.24 %
Kurtosis	--	0.214	-0.444	-0.237

The frequency distribution of observations for the extractives was also examined, as shown in Figure 4.10. As might be expected, the results for this group of chemicals did not display any trend towards a normal distribution. The origin of the extractible chemicals within papermill sludge is not easily identified, however, and is in all likelihood influenced not only by the typical chemistry of the woody chemical component, but also by minute changes in both furnish quality and in process variables.

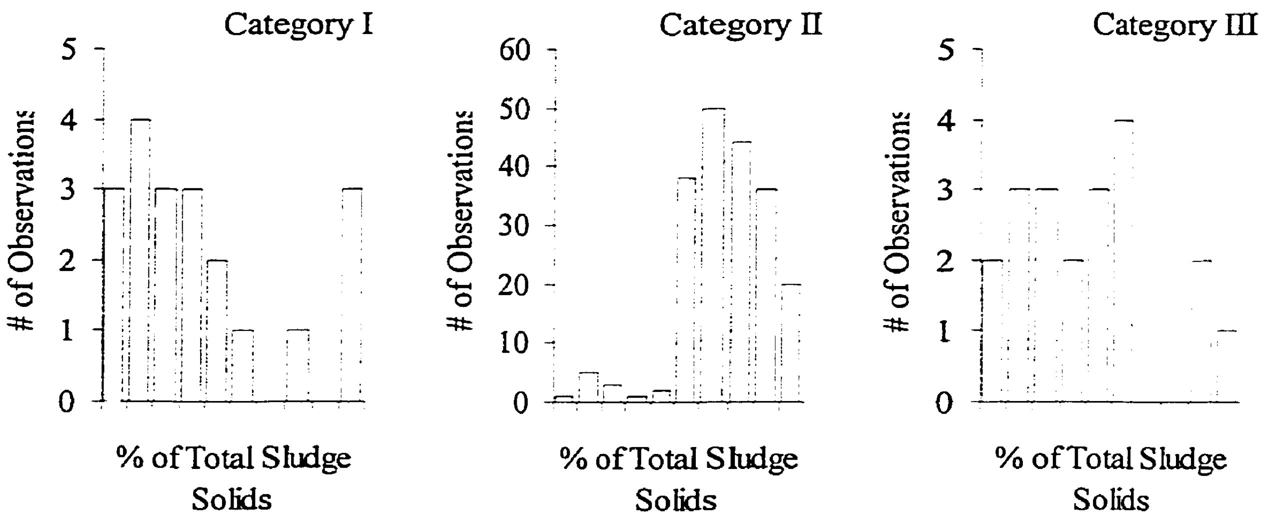


Figure 4.10 Histogram of Extractives observations

The distribution of extractive content within the sludge is typified by large standard deviations, high 95% confidence intervals, and strongly negative kurtosis values, as shown in Table 4.5.

Table 4.5 Factors describing the distribution of extractive observations

	All Mills	Category I	Category II	Category III
Standard Deviation (σ^2)	2.2 %	1.9 %	1.1 %	1.0 %
95% Confidence Interval	0.28 %	0.26 %	0.49 %	0.46 %
Kurtosis	--	1.802	-0.463	-1.213

With the exception of the extractive contents, the frequency distributions of each of the woody organic chemical components of sludge within the provisional category assignments follow a distribution that approximates the normal or t-distribution. In addition, relatively low confidence intervals and values for standard deviation were observed for each of the provisional categories for the holocellulose, Klason lignin, and soluble lignin components of sludge. None of the data collected contradicts the provisional category assignment.

Comparison of sludge inorganic chemical compositions

The inorganic material found in each of the provisional categories of sludge was found to be highly variable. When inorganic material was considered independently, the variation between soluble and acid-insoluble ash content was found to be quite high, as shown in Figure 4.11.

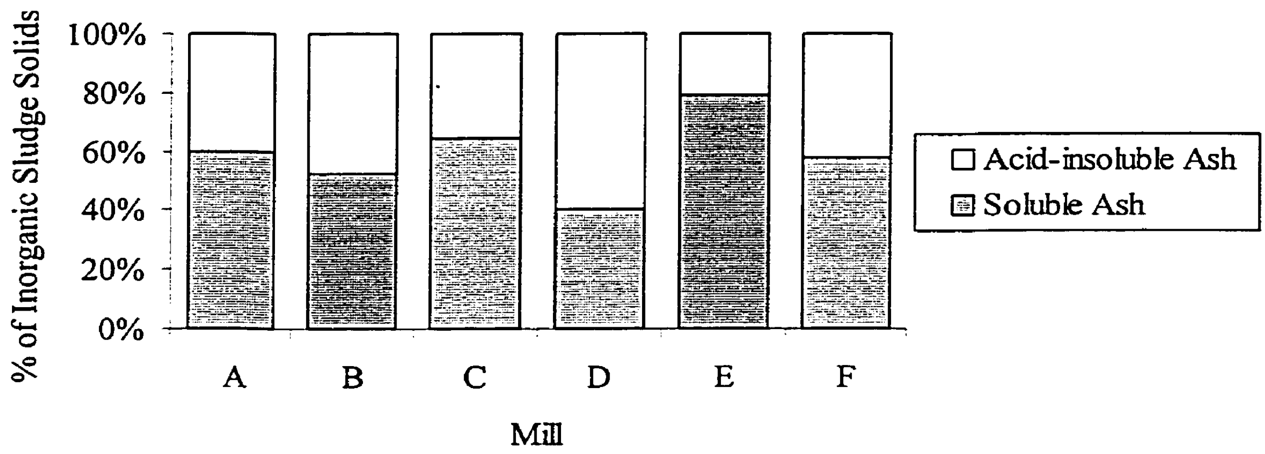


Figure 4.11 Mean inorganic components of papermill sludge, considered independently

The ratios of soluble and acid-insoluble ash displayed in the figure above show little or no relationship with the hypothesized categories assigned earlier. In fact, no relationship can be discerned between these characteristics and mill processes. It is therefore assumed that the presence of soluble and acid-insoluble inorganic components is related to qualities inherent in mill feedstock. Mills A and B, grouped into Category I, show fairly similar inorganic content, and this could be related to the virgin raw material used by each of these installations. The other four installations each use recovered fibre as furnish, and this material is notoriously variable in terms of the presence of dirt and other extraneous materials. The data is summarized in Table 4.6 below.

Table 4.6 Summary of Ash characteristics

Mean (μ)	Acid-soluble Ash$^{\Psi}$	Acid-insoluble ash	Total Ash *(% of Dry Sludge)*
All Mills	61.9 %	38.1 %	16 %
Mill A	59.6 %	40.5 %	8 %
Mill B	52.4 %	47.7 %	17 %
Mill C	64.6 %	35.4 %	16 %
Mill D	40.2 %	59.8 %	12 %
Mill E	78.9 %	21.1 %	23 %
Mill F	57.5 %	42.5 %	21 %

$^{\Psi}$Calculated as Total Ash (100%) – Acid-insoluble Ash

Comparison of the physical properties of sludge fibres

One final analysis technique remains by which the provisional grouping of papermill sludges can be corroborated. An analysis of the physical properties of the woody organic component, i.e. the sludge fibres and fines, may indicate any significant differences among the six papermill sludges tested. Values for length, coarseness, and percent fines are provided in Table 4.7 below.

Table 4.7 Summary of sludge fibre characteristics

	All Mills	**Mill A**	**Mill B**	**Mill C**	**Mill D**	**Mill E**	**Mill F**
Average length (weight-weighted) (mm)	1.68	1.72	1.70	1.66	1.66	1.63	1.65
Average Coarseness (dg$^{\Psi}$)	18.3	22.3	17.5	20.4	16.0	14.3	18.2
Percent fines (length-weighted)	25 %	24 %	25 %	26 %	26 %	25 %	26 %

$^{\Psi}$dg = decagrams of cell wall material. Derived as mg of cell wall material per 100 m of fibre.

From the table above, it is immediately obvious that there is very little actual variation in fibre length between the three mill types. A close examination shows that there is a minute difference between Mills A & B, C & D, and E & F, following the category assignments made in Section 4.4.2. The slight differences that do exist, however, are not statistically significant at $\alpha = 0.05$. The percentage of fines is also statistically similar between each of the six mills. These findings do not corroborate or invalidate the groupings that have been made.

The coarseness of the sludge fibres is found to be quite variable from mill to mill, and between the groups that have been delineated. The values are lower than might be expected in a pure softwood sample, but higher than might be expected in hardwoods. The coarseness values directly relate to the furnish type, and are typical of a mixture of hardwood, softwood, or recovered fibres.

The overall distributions of fibre length are very closely matched between the three tentative categories, as shown in Figure 4.12.

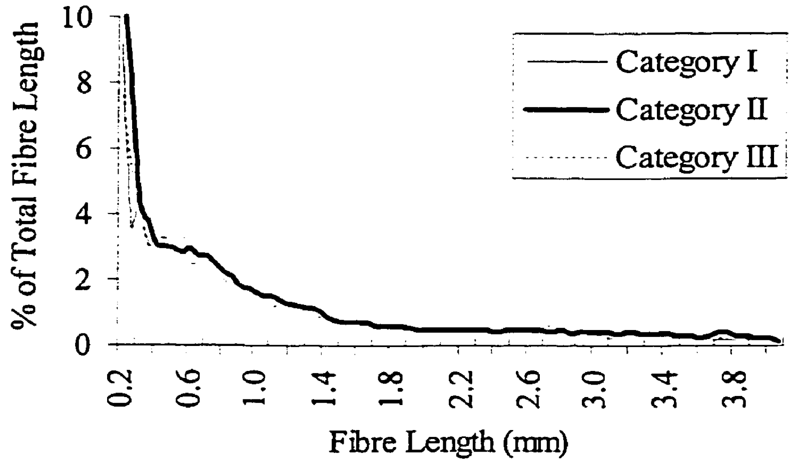


Figure 4.12 Frequency distribution of sludge fibre length

An example of a typical sludge fibre can be found in Figure 4.13. This particular example was obtained from the sludge of Mill B, and was stained with Fast Green in order to improve clarity of the image. The figure illustrates the characteristics of sludge solids, including fibres with broken ends (A), fibre fragments (B), and the presence of fibrous and non-fibrous debris (C). The encrusted debris that surrounds each fibre in the image may not reflect the actual conditions within the solid sludge matrix, but instead may be an artifact of the slide preparation process.

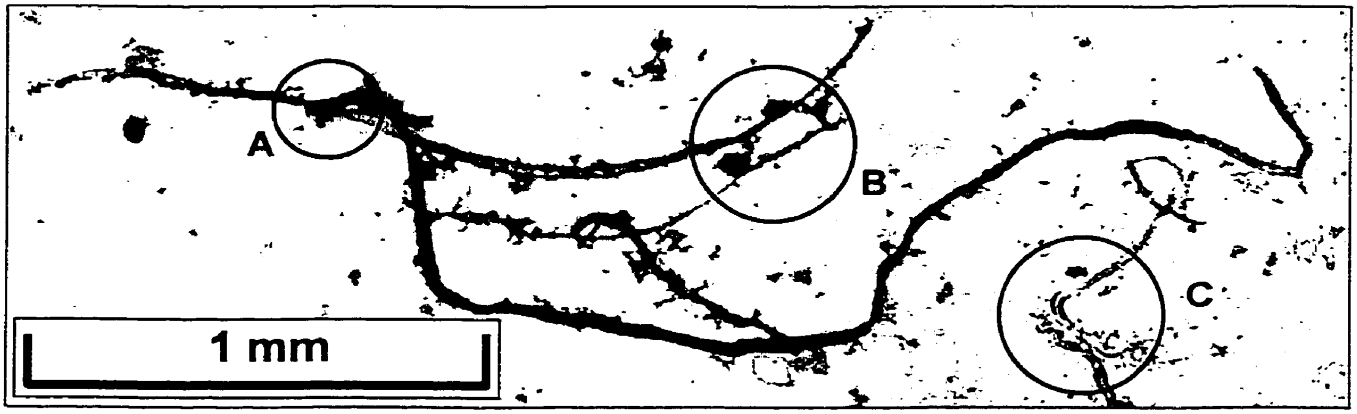


Figure 4.13 Long fibre remnants in papermill sludge (Mill B)

The results of testing indicate that sludge fibres have very similar properties, despite the process or furnish used to create these fibres. Thus, the assignment of mills to categories based upon the macro characteristics of sludge is not invalidated, although not corroborated in any way.

4.4.4 Summary of Analysis

There is convincing evidence that papermill sludge can be grouped according to mill types. The physical and organic chemical characteristics of sludge have been found to support the suggested grouping, with a clear delineation shown between virgin pulp mills, recycling mills that do not utilize deinking, and recycling mills that do use deinking.

There was no evidence produced to contradict the assigned groupings. A review of the inorganic chemistry of each papermill sludge type, however, did not corroborate the selection of these categories. Since the inorganic composition of sludge is of secondary importance to this thesis, further investigations were not undertaken at this time. Of primary importance is to identify and model the role of woody organic material within papermill sludge, and the results of testing supported utilizing the proposed mill categories as part of a predictive tool for this material.

The woody organic chemistry of papermill sludge is visually presented in the following graph.

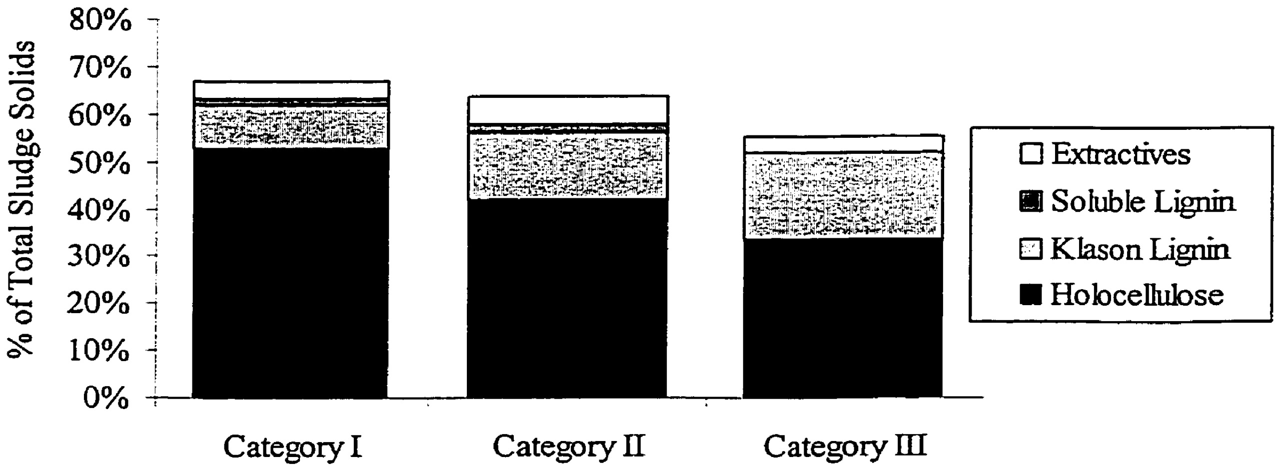


Figure 4.14 Woody organic composition of papermill sludge by mill category

Sludge originating from mills in Category I contains approximately 67% woody organic material. Sludge originating from mills in Category II contains slightly less woody organic material at 64%, while Category III mill sludge contains only 55%. These differences are based upon the actual wood chemical components of holocellulose, Klason lignin, Soluble lignin, and extractives, which are each significantly different in the three mill categories ($\alpha = 0.1$).

4.5 Conclusions

The principal conclusions that can be drawn from this chapter are:

1. An observation of the variability of woody organic components within papermill sludge over time reveals that alphacellulose is the most variable component found within sludges. Very long term observations confirm that changes in process or furnish can greatly influence the woody organic chemistry of papermill sludges.

2. Three mill categories can be identified through the macro characteristics of papermill sludge. These categories are: virgin pulp mills, recovered paper mills without deinking, and recovered paper mills with a flotation deinking stage.

3. The woody organic chemical components of sludge correspond to these categories. Observed levels of holocellulose, Klason lignin, and soluble lignin, as measured in sludge from multiple mills within these categories, follow a normal or t-distribution, indicating that the samples resemble a normal population.

4. The inorganic components of sludge do not correspond to the proposed grouping, but are considered of secondary importance to the entire study.

5. The physical characteristics of papermill sludge fibres, in terms of length and percent fines, do not change significantly from mill to mill. The coarseness of fibres within papermill sludge is variable, and reflects differences in furnish and in processing.

6. The woody organic component of sludge is significantly different in the three mill categories described, comprising 67% of Category I sludge, 64% of Category II sludge, and 55% of Category III sludge.

5 Development of a predictive model for pulp and paper production, consumption, and recycling

5.1 Introduction

In order to describe the proportion of organic material contained within sludge on a global scale, it is necessary to understand the driving factors behind global sludge production.

5.1.1 Abstract

Papermill sludge production is directly related to the production of virgin and recycled pulp, paper and paperboard products. Future trends in the production, use and recycling of pulp and paper products can in turn be shown to be dependent upon supplies of raw material, and upon the characteristics of the population that manufactures and uses these products. Three output factors (paper production, consumption, and recycling) were compared to six discrete input factors (fibre supply from forests, plantations, and nonwoods, population, population density, and literacy). A regression model was constructed that identified the pertinent input variables on a national basis. The input variables were shown to be distributed in distinct geographic groupings. Population variables were most important in developing countries, where rapidly changing populations are driving paper manufacture and use. Fibre supply variables are found to be more important in the western hemisphere, where large forests are being managed for fibre supply. Plantation and nonwood fibre supply is most important in the southern hemispheres where climate is more suitable for the development of these ventures. The proposed models for paper production and wastepaper recycling were very successful, accounting for 94 and 96% of global totals in the baseline year. The proposed model for paper consumption was less successful, with only 81% of global consumption accounted for in the baseline year.

5.1.2 Objectives

The overall objective of model development is to account for the variables that drive paper production, consumption, and recycling at the national level. The specific objectives of this portion of the study are to:

1. Identify discrete input variables that relate to pulp and paper production, consumption and wastepaper recycling;
2. Quantify the historical trends described by each of the input variables identified, and extend these trends to the year 2050;
3. Relate the trends described by each variable to the historical production, consumption and recycling of paper and paper products on a national basis, and;
4. Verify the validity of the model by correlating projected data to historical data, and by comparing global outputs to the model scope.

5.1.3 Disclaimer

The work in this chapter builds upon work originally conducted by the author at the Food and Agriculture Organization of the United Nations (FAO). Portions of the work have been previously published in Unasylva (Mabee 1998) and in working papers by the author (Bull et al. 1998b, Mabee and Pande 1997). An early version of the model was included in the Global Fibre Supply Model, which was released worldwide by the FAO in 1998 (Bull et al. 1998a).

5.2 Definition of model parameters

5.2.1 Identification of output variables

The quantity of sludge being produced is directly correlated to the amount of paper manufactured. As was made clear in Chapter 4, the characteristics of sludge change depending on whether virgin or recovered fibre is used as a source of raw material. The wastepaper recycling rate reflects the total amount of paper and paperboard consumed nationally. Given these facts, it is possible to identify three principal output variables.

1. National production of paper and paperboard;
2. Rate of wastepaper recycling, and;
3. National consumption of paper products.

Each of these output variables can be linked and compared with historical datasets, which are included in model development and are later used for model validation.

5.2.2 Identification of input variables

Some of the discrete variables that affect pulp and paper production and consumption, as well as wastepaper recycling, are shown in Figure 5.1 on the next page.

The discrete variables illustrated in Figure 5.1 can all be described using established historical datasets. To a varying extent, each of these factors has an impact on the three output variables defined in the previous section. The strength of this impact is hypothesized by the placement of variables within the diagram.

The suggested variables can be initially divided into primary and secondary categories. The primary variables are those related to fibre supply and population. These variables are simple measurements of quantities within the country itself, which are less subject to fluctuation due to external influences, such as economic depression or shifts in global market demands. The secondary variables include indicators of economic health, such as GNP, as well as imported supplies of raw materials. These variables are influenced as much by international events as by national trends.

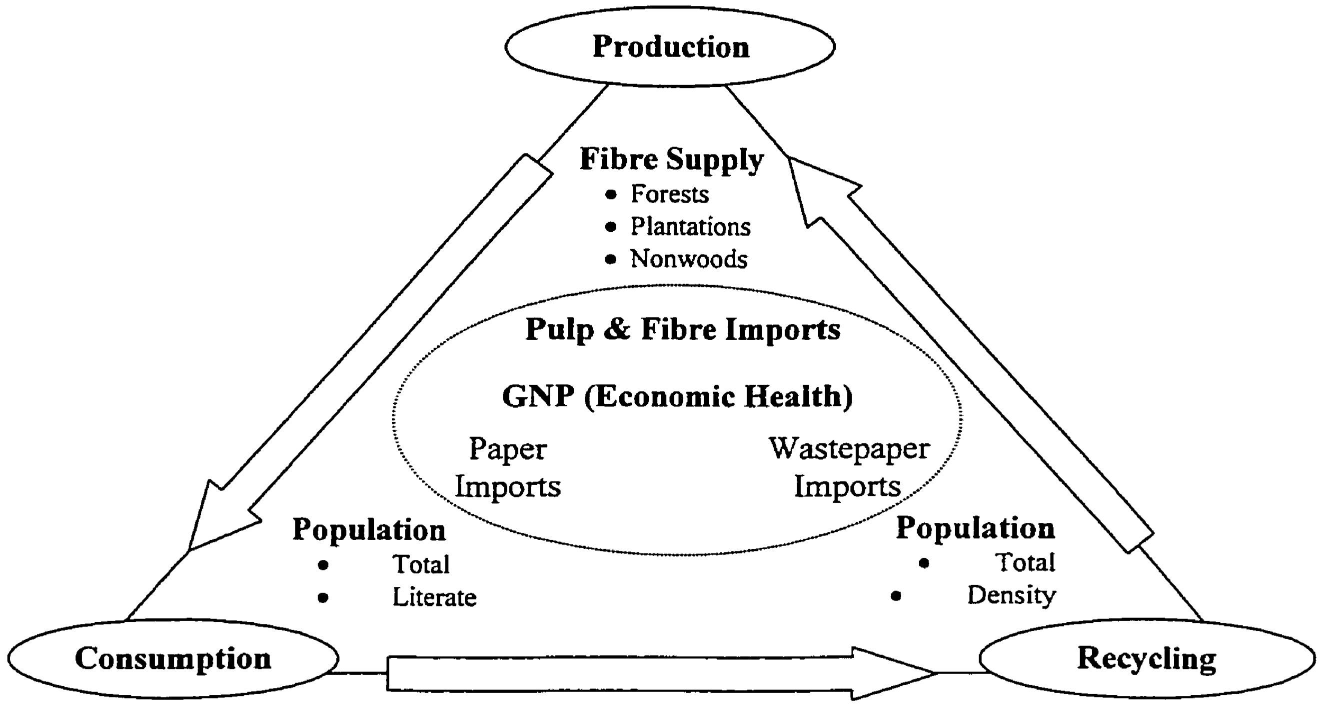


Figure 5.1 Variables that affect paper production, consumption, and recycling

Primary input variables

Fibre supply

Fibre supply is a factor that is most directly related to pulp and paper production, since without adequate sources of fibre, the manufacture of pulp or paper is physically impossible. Fibre can be supplied through domestic markets or through trade. It may be supposed that having an adequate supply of fibre will also influence the consumption of paper and paper products, as paper should be widely available at low cost to the consumer. It may also be hypothesized that wastepaper recycling may be related to the amount of virgin fibre available domestically, as nations with a surfeit of virgin fibre may have less economic or environmental incentive to recover and recycle paper.

Fibre supply has been identified as having four or five principal components in several international studies, including the Global Fibre Supply Model (GFSM) released by the FAO (Bull et al. 1998a). These components include forests (both undisturbed and disturbed by human influence), plantations, and nonwood fibres. Each of these components can be considered a separate variable, which can influence the overall production, consumption, or recycling of paper.

A fifth component of fibre supply, that is not considered here, is the amount of recovered fibre available on the open market. As wastepaper recycling is a desired output of the current model, this component is not considered as an input variable.

Population characteristics

An important factor relating to pulp and paper consumption is the population of the country, and the characteristics of that population. Consumption trends will be heavily affected by positive or negative gains in population over time, as more people can consume more products. A larger population also increases the likelihood of developing domestic manufacturing installations, which will have an impact upon the production of paper and paper products. Large populations also may increase the chances of paper production and recycling, as the demand for paper and recycled products will rise with population. Supplies of waste paper for recycling are also more likely to exceed the minimum economic threshold necessary to make recycling ventures profitable, provided that a large enough population is generating waste paper.

An educated population is more likely to consume paper and paper products. A proxy for measuring education is to consider the literacy rates within the country. Educated people are more likely to have disposable incomes necessary to purchase packaged goods, and are more likely to spend on books, magazines, diapers, and other paper products.

Population density is also quite important, particularly in regards to waste paper recycling. Recycling programs are only economically feasible in high-density populations, and then only when the population is high enough to provide an adequate supply of raw material. Accordingly, the percentage of urban population is an important factor in determining waste paper recycling potential.

Secondary input variables

Economic health of the nation

The construction of mills to manufacture virgin or recycled paper products requires a high level of capital investment. Domestic or international corporations are less likely to embark on such a venture if the economy of the nation in question is poor. The economic health of a country is also an indicator of the personal wealth of a country's citizenry, and describes the potential domestic market for paper products. It is therefore not unreasonable to consider the economy as equally important to paper production, consumption, and recycling, as shown in Figure 5.1. The economic health of a country can be estimated through the analysis of a variety of statistics, including the Gross National Product (GNP).

Raw material imports

A sufficiently wealthy country can afford to supply its citizenry with paper products, and its mills with raw material, by purchasing commodities such as fibre, pulp, paper, or wastepaper on the international market. The ability of a country to do this is related directly to the purchasing power of its currency, and to the economic robustness of its domestic economy. Imports make up an important part of fibre supply in many countries, particularly in continental Europe and Asia.

Problems with secondary input variables

The difficulty with using GNP as a variable in predicting fibre supply is this factor combines both financial and social values, and is subject to both domestic and international influences. The combination of values from a variety of sources means that the final GNP figure can show large fluctuations from year to year. In order to compare GNP values from a variety of countries, conversions must be made to a single currency, which further compounds the possibility for error. More comprehensive measures of economic welfare are available for some countries, but are not widely tabulated by the World Bank or by independent auditors (Blomqvist et al. 1987).

Similar problems are evident when examining the usefulness of raw material imports as a variable. Much of the historical data that exists describing fibre, pulp, paper, or wastepaper imports is based on estimates, as the original data are collected using a variety of measures (dollar values, volume and mass measurements) that must be standardized before the national total can be calculated. The ability of a nation to afford these imports is based upon the economic health of the country, which is related to both international as well as domestic affairs. The definitions for pulp and paper products are not always standard from country to country, and thus there is an additional possibility for error. Furthermore, the model when fully developed will not include every country in the world due to incomplete data, and thus cannot be balanced for imports and exports.

Indiscrete input variable

Occasionally, statistically significant trends will be identified in the historical data of production, consumption, or recycling that may not display a significant correlation to any of the discrete input variables that have been listed within this section. In anticipation of this eventuality, it is proposed that time be included as an indiscrete input variable. Thus, changes that cannot be explained by the input variables identified, such as increasing rates of wastepaper recycling due to policy implementation, can be linked to year rather than ignored by the model.

Summary

The set of discrete input variables has been described. A range of problems has been associated with the secondary input variable group; these problems stem from the fact that these variables reflect international as well as national trends. In order to avoid possible errors within the modeling exercise, the decision has been made to concentrate upon the primary variables identified above, with the inclusion of time as an indiscrete variable. Therefore, it is possible to define the input variables as follows.

1. Year
2. Fibre supply available from forests (undisturbed and disturbed);
3. Fibre supply available from plantations;
4. Fibre supply available from nonwood sources;
5. Total population of the nation;
6. Literate population of the nation, and;
7. Urban population of the nation.

5.2.3 Development of the model expression

The model is a multiple regression equation that utilizes sub-functions to describe each of the discrete input variables listed in the previous section. Given the input and output variables defined in the two sections above, it is possible to write the basic model function as follows.

Equation 5.1

$$P, C, R = m_1 x + m_2(FO) + m_3(IP) + m_4(NW) + m_5(TP) + m_6(DP) + m_7(LP) + C$$

where
P = Paper and paperboard production
C = Paper and paperboard consumption
R = Paper and paperboard recycling
x = year
$m_1 - m_7$ = Coefficients corresponding to each model element
C = Constant

and where six sub-functions are defined as
FO = Fibre available from forests
IP = Fibre available from industrial plantations
NW = Fibre available from nonwood sources
TP = Total population
DP = Population density
LP = Literate population

5.3 Historical data collection

The historical data was collected in an SQL database designed for the modeling exercise. For each of the subtitles listed in this section, a single table was created in which individual records were identified by country code, data reference year, and data reference code. Each unique record was assigned a code, and estimated data points were noted within the database.

5.3.1 Paper production, consumption and recycling

The historical data available for global paper production, consumption, and recycling is available from three principal sources.

The Food and Agriculture Organization of the United Nations has collected data on these commodities for several decades, and this data is available on-line through FAO Stat or in print through the FAO Yearbook of Forest Products (published annually) (FAO 2000, FAO 1999b, FAO 1998, FAO 1997, FAO 1996, FAO 1995, FAO 1994, FAO 1993, FAO 1992, FAO 1991, FAO 1990). FAO data is collected through government reports and is analyzed by experts in the field of pulp and paper before it is published. Estimates are included in these datasets where actual data is not available, based upon the best knowledge at the time of publishing. These estimates can be updated from year to year as new information is made available, which is why it is important to check each subsequent release of statistics.

Pulp and Paper International, a widely-read peer reviewed journal, also publishes a yearly summary of pulp and paper activities, including the relevant data on trends (PPI 2000a, PPI 2000b, PPI 1999a, PPI 1999b, PPI 1998, PPI 1996, PPI 1997, PPI 1995, PPI 1994, PPI 1993, PPI 1992, PPI 1991, PPI 1990). The data collected by this journal also includes government data, but relies heavily upon input from the pulp and paper industry. Data submitted are peer reviewed and summarized by country. Again, estimates are included where no data is available, and these estimates are updated on an annual basis when new information is made available.

Finally, datasets are occasionally available from national-level organizations or from national governments. When these datasets were available, they were utilized in both model development and in data validation. An example of these datasets is the Reference Tables report published annually by the Canadian Pulp and Paper Association (CPPA 1999).

5.3.2 Fibre available from forests

The values for forest fibre available for supply are provided in cubic metres, and are taken from the Global Fibre Supply Model (GFSM) published by the FAO in 1998.

In order to determine the amount of forest-grown fibre available for supply, it was necessary to assess the total forest area, the total and commercial volumes of existing forest, the removal rate currently employed, and the increment or additions to the forest. Data was collected from a number of sources, which were classified as primary, secondary, or tertiary. Primary sources documented on the ground reviews of standing timber, usually conducted as part of a government or industry review of forest inventory. Secondary sources quoted primary reports, and were the most common literature source found. Examples of secondary reports include government yearbooks describing forest activities, or secondary reports. Tertiary sources include unsubstantiated data on forest inventory or growth. These reports were used to verify data in primary and secondary sources, or as guidelines in the establishment of estimates.

When the data were fully collected, a country assessment team consisting of experts from the FAO as well as from the nation in question was gathered to assess the information. In some cases, data could be compared with GIS-based data collected as part of the Forest Resource Assessment 2000 initiative also ongoing at the FAO. In other cases, best estimates had to be made using the expertise available. As many countries do not declare their statistical assumptions in defining their forest inventories, extensive efforts had to be made to validate data. Critical issues still remain in the definition of commercial species, volume expansion factors, and wood increment values (Bull et al. 1998a;Bull et al. 1998b).

When assessment of the data was complete, official GFSM estimates were made of forest area and growth. These estimates were made at the closest possible resolution, given the available data. In Brazil, for instance, six forest types were identified and separate values for growth, yield, and areas were used within each of these six forest types. Thus, when fibre supply is calculated at the national scale the figure better reflects the dynamics of forest cover in different ecoregions within the country (Bull et al. 1998a;Bull et al. 1998b).

5.3.3 Fibre available from plantations

The values for plantation-grown fibre available for supply are provided in cubic metres, and are taken from the Global Fibre Supply Model (GFSM) published by the FAO in 1998.

In order to determine the amount of plantation-grown fibre available for supply, it was necessary to assess the total area available for industrial plantations, the rate of plantation establishment, the conversion of forest to plantation area, the species groups used, and the possible gains associated with improved silviculture and genetic manipulation of growing stock. As with all assessments carried out in the GFSM, a variety of data sources were examined and classified according to the primary, secondary, and tertiary system employed with forest data (see Section 5.3.2). A country assessment team was assembled, consisting of experts from the FAO and from the country in question, when possible.

Critical issues in data validation were centered upon the definition of plantations, the growth rates associated with various species groups, and the effects of successive plantations on soil quality and fibre yield. As before, an official GFSM estimate of plantation area, rates of establishment, and growth were made by the assessment team. These estimates were based on plantation species groups being used within the country, in order to improve data resolution Bull et al. 1998a;Bull et al. 1998b).

5.3.4 Fibre available from nonwoods

The values for nonwood-grown fibre available for supply are provided in cubic metres, and are taken from the Global Fibre Supply Model (GFSM) published by the FAO in 1998. The term nonwood, as used here, refers to specialty-grown annual plants, such as hemp or kenaf, as well as agricultural waste such wheat or rice straw.

In order to determine the amount of nonwood-grown fibre available for supply, international experts were brought in to assess the potential fibre supply available from nonwoods based upon pulping capacities. As with all assessments carried out in the GFSM, a variety of data sources were examined and classified according to the primary, secondary, and tertiary system employed with forest data (see Section 5.3.2). The experts were then given the task of determining the official GFSM estimate.

Critical issues were identified in relation to pulping efficiency, gains in technological expertise, and crop substitution. GFSM estimates of nonwood-grown fibre availability were based upon existing trends in nonwood pulping capacity, which represent investments in equipment that differs from traditional woody pulping technology. The role of nonwoods was found to play a small but significant role in global fibre supply, particularly in parts of Asia and Central America (Bull et al. 1998a;Bull et al. 1998b).

5.3.5 Population trends

The Population Division of the United Nations Secretariat prepared the estimates and projections of total population utilized in this study. These estimates are revised every two years in order to incorporate new data. In general, these population figures are estimates of persons resident in the country or area at mid-year. They are usually based on population census data adjusted to the specified year, taking account of birth, death and international migration rates as determined from population surveys and registers and other national sources as available. Short-term residents and visitors in the country or area for less than one year are usually excluded. The most recent estimates of population were made for the year 1999 (Population Division of the United Nations Secretariat 2000a, Population Division of the United Nations Secretariat 1999, Population Division of the United Nations Secretariat 1998, Population Division of the United Nations Secretariat 1997, Population Division of the United Nations Secretariat 1996a, Population Division of the United Nations Secretariat 1996b, Population Division of the United Nations Secretariat 1995).

5.3.6 Population Density

The Population Division of the United Nations Secretariat originally made the estimates of rural and urban population percentages utilized in this study. Reports detailing world changes in population and trends towards urban or rural population are published every two years. The data presented is based on national census or survey data that has been evaluated and, whenever necessary, adjusted for deficiencies and inconsistencies by professionals working on behalf of the United Nations. Urban-rural classification of population in internationally published statistics follows the national census definition, which differs from one country or area to another. National definitions are usually based on criteria that may include any of the following: size of population in a locality, population density, distance between built-up areas, predominant type of economic activity, legal or administrative boundaries and urban characteristics such as specific services and facilities. For the purpose of this study, the exact definition of urban and rural populations is not of primary importance. Rather, trends illustrated towards one or the other extreme are of interest, as an increasingly urban population may have more need for and exposure to paper and paper products.

The approach used in estimating rates of population density change is one of continuous growth, which considers that population grows exponentially. The most recent estimates were made in the year 2000 (Population Division of the United Nations Secretariat 2000b, Population Division of the United Nations Secretariat 2000a, Population Division of the United Nations Secretariat 1997, Population Division of the United Nations Secretariat 1995).

5.3.7 Literacy

All literacy data used in this study were compiled by the United Nations Educational, Scientific and Cultural Organization, and hosted by the United Nations Statistical Division. Regional specialists working within the UN system made professional estimates of literacy for most of the world's countries. The most recent estimates were made for the year 2000. Other estimates are available for many countries at intervals of 5-7 years. UNESCO does not provide estimates of literacy for many developed countries. In these cases, estimates of literacy were put at 99%, as adult illiteracy is considered eliminated in these nations (UNESCO Institute for Statistics 1999;UNESCO Institute for Statistics 1998;UNESCO Institute for Statistics 1996;UNESCO Institute for Statistics 1995a;UNESCO Institute for Statistics 1995b).

The restrictions put on literacy data used in this study were that all countries considered have more than 3 data reference points, and that these data series show low variation. As the same UN Organization compiled all data points for each country, the data series were very homogenous.

The literacy data utilized here should be treated with some suspicion, as verification of this data is impossible in the scope of this thesis. The figures provided by UNESCO are widely quoted, as this organization is the primary global caretaker of these types of statistics

5.4 Development of discrete input variables

5.4.1 Definition of future scenarios

To create a range of possible future values for paper and paperboard production and consumption, and for wastepaper recycling, separate calculations were made for each of the discrete variables identified in Section 5.2.2. These calculations were based on three future scenarios, which provide a range of future values for each of the six variables. These futures were defined by taking a philosophical approach, and are as follows.

1. The 'status quo' future. Current trends in fibre supply from forests, plantations, and nonwood sources continue without any deviation. Population growth continues at the current rate, and trends in literacy and in urbanization continue as they have in the past.

2. The 'industrial' future. Fibre supply from forests is increased and plantation establishment rates increase exponentially. Nonwood supplies of fibres are increased as companies implement technological changes to take advantage of this source of fibre. Population growth increases at a rate exceeding the current trend as technological advancements make increased populations more sustainable. Urbanization increases above the current trend as more people move to cities to seek employment. Literacy rates decrease as rising populations put pressure on social systems.

3. The 'green' future. Fibre supply from forests is decreased as the amount of forest land under protection increases. Plantation establishment is increased over the current rate, but to a lesser extent than in the industrial future due to lack of available land. Nonwood supplies of fibres are decreased as the older technology is phased out of service. The rate of population growth declines under the current trend as spending is directed towards social programs and education. This also sparks a rise in literacy rates. Less technological development reduces the rate of urbanization.

It is important to note that these futures are entirely arbitrary in nature. The model is designed to be flexible, and to allow the user to create unique scenarios that reflect individual requirements. The exact parameters that each future curve follows will be discussed in the sections that follow.

5.4.2 Fibre available from forests

Equation of fibre supply

The first discrete variable encountered in the overall model is *f* (FO), or the function describing fibre available from forests. This function is based on work previously published as part of the GFSM (Bull et al. 1998a). In order to determine fibre supply, equations that define harvest levels based on volume were established. The equation of the forest fibre supply line is shown in Equation 5.2.

Equation 5.2

$$F = \frac{H \cdot A_{UD}}{C_C} + (i \cdot A_D)$$

where

F = Fibre available from forests (m^3)
H = Harvesting intensity (m^3.ha/a)
C_C = Cutting cycle (a)
A_{UD} = Forest area, undisturbed by human influence (ha)
A_D = Forest area, disturbed by human influence (ha)
i = Mean annual increment (m^3/ha)

The first half of Equation 5.2 refers to the undisturbed forest area. In these areas, the sustainable harvest level is more closely related to the cutting cycle and harvest intensity than to mean growth indicators. This is because many undisturbed forest areas around the world are associated with mature or over mature forest types, where annual growth is minimal. The second part of the equation refers to the disturbed forest areas within a country, where forest ages tend to be younger. In these areas, the growth rates reflect the establishment and growth of the forest. Note that the second half of the equation essentially defines the sustainable harvest level, as it only takes into account the annual increment of growth.

The variables for forest areas can be further defined as shown in the two equations below.

Equation 5.3

$$A_{UD} = A_{TF} - A_D - A_{LP} - A_{EI}$$

Equation 5.4

$$A_D = (A_{TF} - A_{UD} - A_{LP} - A_{EI}) \cdot [1 - (d/100)]^{Year-1980}$$

where

A_{TF} = Total forest area (ha)
A_{LP} = Legally protected forest area (ha)
A_{EI} = Economically inaccessible forest area (ha)[1]

---

[1] Economically inaccessible forest area include forest areas that are too remote for harvest, forest areas on slopes too steep for harvest, and forest areas with rotation ages > 300 years.

d = Deforestation rate (+ve) or afforestation rate (-ve) (% based on # of ha from 1980 - 2000)

The forest areas available for harvest are therefore directly related to the legally protected forest area, as well as to the economically accessible forest areas at the time of the assessment and to the deforestation rates observed within that forest type. The deforestation rate as used is based on data collected for the Forest Resources Assessment (FRA), as carried out by the FAO in 1980, 1985, 1990, 1995, and 2000. Here, deforestation is meant to refer to forest land being converted into non-productive land through poor harvesting practices, or through conversion to agricultural or urban areas with a permanent crown cover of less than 10% (Bull et al. 1998b). The overall rate is pro-rated to 1980 in order to provide a consistent view of trends for both historical and projected data.

Future definitions

Given the equations above, three scenarios of fibre supply from the forest can be defined.

1. Deforestation rates continue along historical trends. The average cutting cycle used in the nation will continue to be implemented. The legally protected forest area within the country will stay the same.
2. Deforestation rates will increase by 10%. The average cutting cycle will be reduced by 5 years, providing more timber in the short term. The legally protected area of the country will be increased by 10% over its current land base.
3. Deforestation rates will decrease by 10%. The average cutting cycle will be increased by 5 years, providing less timber but preserving more of the forest. The legally protected forest area of the country will be increased by 20% over the current area thus protected.

Model outcomes

Three examples of model outputs are given in Figure 5.2, Figure 5.3, and Figure 5.4. These graphs illustrate three patterns of future fibre supply from the forest.

The first common pattern of future fibre supply is marked by rapid decrease in available fibre. This is well illustrated in Figure 5.2, which describes future fibre supply trends for Malaysia. In each of the three scenarios, fibre supply drops extremely over the first 10 years or so of the outlook. This is because the amount of undisturbed forest available for harvesting has dropped drastically within this country.

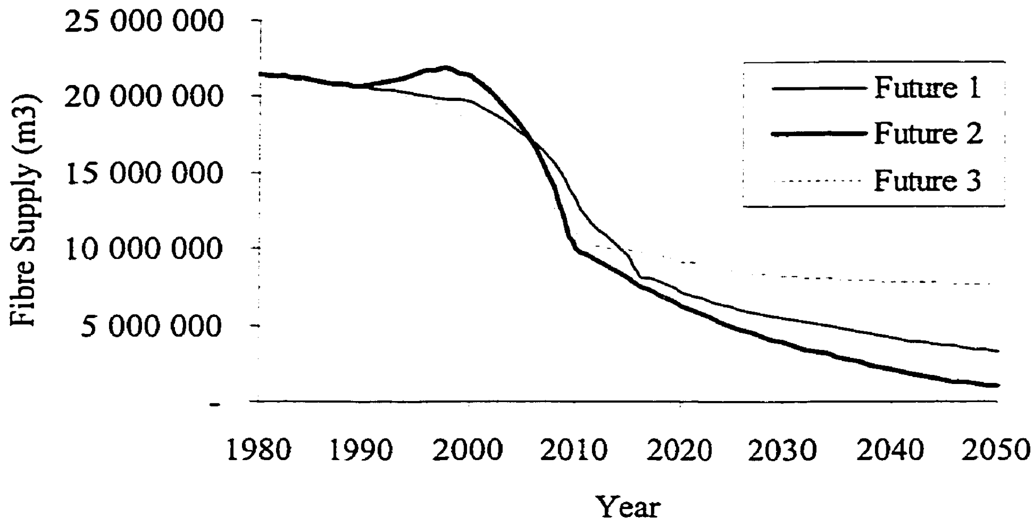


Figure 5.2 Projected fibre supply from forests, Malaysia (1980 - 2050)

In the graph above, it can be seen that fibre supply can be stabilized to some degree by decreasing rates of deforestation. Scenario 3, in which deforestation rates are relaxed substantially by 2050, shows markedly higher fibre supply curves in the future than do the other futures, in which fibre supply consistently drops towards zero. It can also be seen that short-term gains in fibre supply that are achieved by liquidating undisturbed forest area, as shown by Future 2 in particular, results in long-term loss of fibre supply due to loss of productive forest land.

The second common pattern of future fibre supply is that of steady state. The amount of fibre available in Canada, as shown in Figure 5.3, is not predicted to rise or fall to any great extent over the next 50 years. A slight decline in fibre supply associated with Future 3 is likely related to the establishment of additional protected areas. The actual deforestation rate in this country is very low, as little forest land is currently being converted to urban or agricultural land; in actual fact, Canada has experienced positive afforestation over the past 20 years.

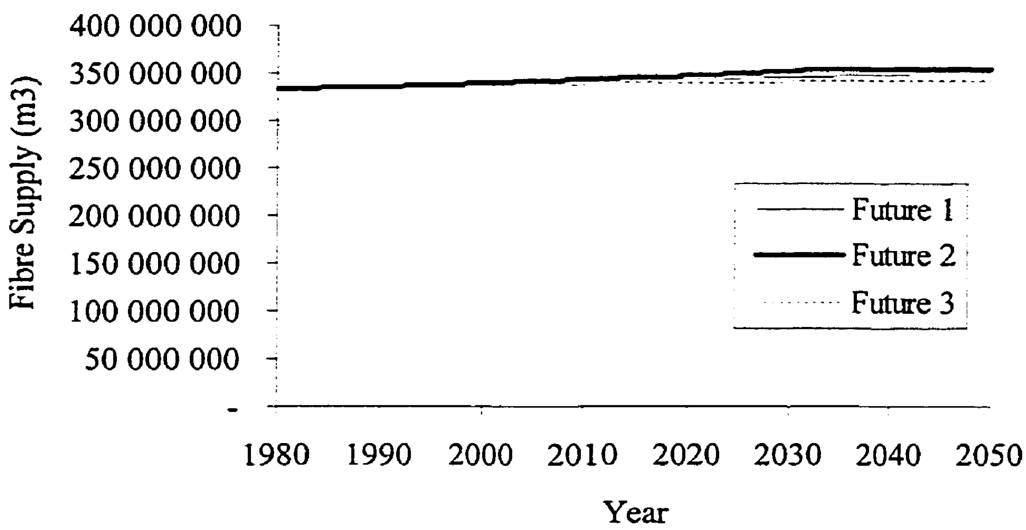


Figure 5.3 Projected fibre supply from forests, Canada (1980 - 2050)

The third common pattern associated with future scenarios is that of a fairly level supply, marked by a sharp drop in overall supply as undisturbed forest stock runs out but remaining fairly level as the projection continues. In some cases, the harvesting of the remaining vestiges of the natural forest results in a significant increase in short-term fibre supply, followed by a significant drop as the available natural forest reserves are converted to disturbed or unforested area. In Figure 5.4, future fibre supply for Brazil is shown. Only in Future 2, which describes an industrial scenario characterized by high deforestation rates, does the fibre supply drop significantly. In the more environmentally optimistic scenario described by Future 3, fibre supply remains steady as deforestation rates decline.

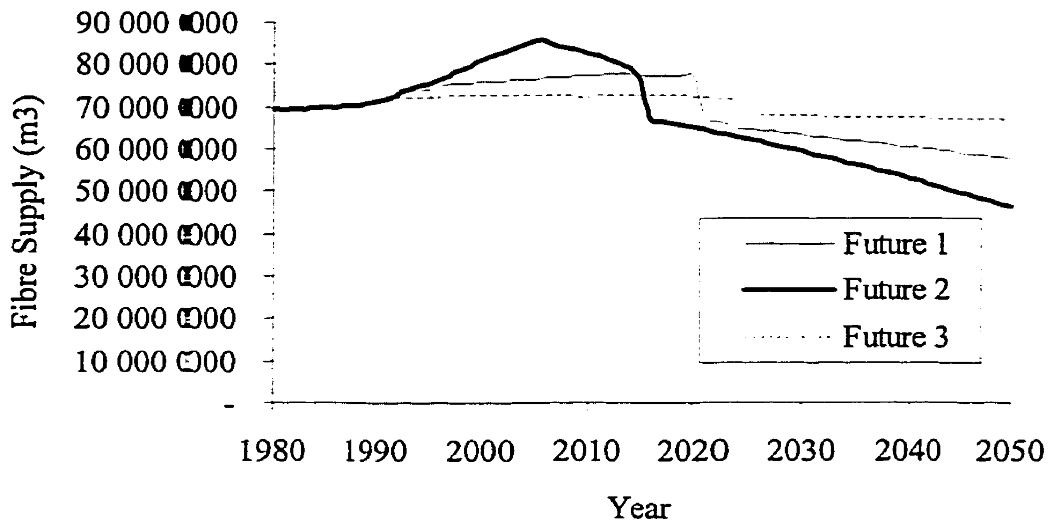


Figure 5.4 Projected fibre supply from forests, Brazil (1980 - 2050)

5.4.3 Fibre available from plantations

Equation of fibre supply

The second discrete variable encountered in the overall model is f (IP), or the function describing fibre available from industrial plantations. The term industrial is included here to differentiate those plantations grown for wood supply from those plantations planted for other purposes, including soil stabilization and agroforestry. This function is based on work previously published as part of the GFSM (Bull et al. 1998a). In order to determine fibre supply, equations that define harvest levels based on volume were established. The equation of the plantation fibre supply line is shown in Equation 5.5.

Equation 5.5 $$IP = [i \cdot (1+g)] \cdot A_P$$

where
IP = Fibre available from industrial plantations (m^3)
i = Mean annual increment (m^3/ha)
g = Gains in increment due to improvements in silvicultural practices or genetic gains (%)
A_P = Area of industrial plantations (ha)

In this equation, the variable for plantation area can be expanded as follows.

Equation 5.6 $$A_p = A_p \cdot (1 + (a/100))^{Year-1980}$$

where
a = Afforestation rate (% based on # of ha from 1980 - 2000)

As shown in Equation 5.6, the afforestation rate is the key controlling factor in determining the area of plantations contributing to fibre supply.

Future definitions
Given the equations above, the three scenarios of fibre supply from industrial plantations can be defined as follows.

1. Afforestation will continue at historical rates. Increment gains, which reflect improvements in silvicultural practices and genetic stock, will not result in any increase in plantation yield over the next 50 years.
2. Afforestation rates will increase by 5% from the year 1995 until the year 2010, or until the maximum amount of land available for plantations is reached. Increment gains will result in a 50% gain in plantation yield.
3. Afforestation rates will decrease by 5% from the year 1995 until the year 2010. Increment gains will result in a 5% gain in plantation yield.

Model outcomes
The model outputs for plantation fibre supply were very homogenous, with most countries showing a remarkable increase in future fibre supply. A typical example of the model output is shown in Figure 5.5. In Indonesia, output from plantations is anticipated to increase by at least 100% over 2000 levels.

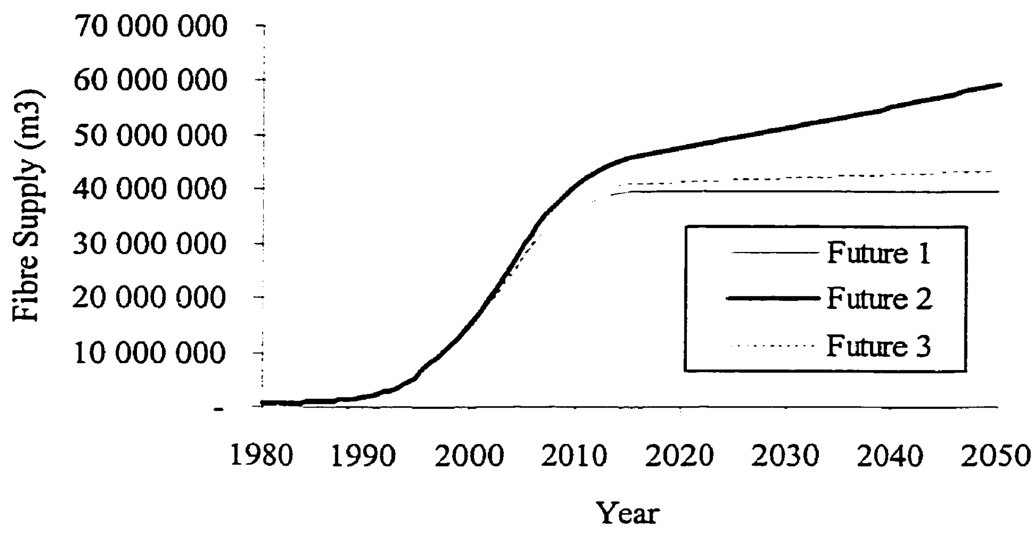


Figure 5.5 Projected fibre supply from industrial plantations, Indonesia (1980 - 2050)

With increases in genetic stock potential or in silvicultural practices, the total amount of fibre available from plantations can rise dramatically beyond the current trends. This is best illustrated by Future 2, which shows significant gains over current trends in industrial plantation fibre output. Even in Future 3, where afforestation rates are anticipated to decrease, the modest gain assigned from improved silviculture will improve fibre yield over the current baseline trend illustrated by Future 1.

5.4.4 Fibre available from nonwood sources

Equation of fibre supply

The third discrete variable encountered in the overall model is f(NW), or the function describing fibre available from nonwood fibre sources. This function is based on work previously published as part of the GFSM (Bull et al. 1998a, Mabee and Pande 1997). The fibre supply of nonwoods was based on the technological capacity of the country to process agricultural wastes such as wheat and rice straw, or specialty annual plants such as kenaf or hemp. The equation of the nonwood fibre supply line is shown in Equation 5.7.

Equation 5.7 $$f(NW) = (C_{\%NW} / 100) \cdot P_{TC}$$

where
NW = Fibre available from nonwood sources (MT)
$C_{\%NW}$ = Total nonwood pulping capacity (% based on nonwood pulping capacity/total pulping capacity)
P_{TC} = Total pulping capacity (MT)

Future definitions

Based on the equation given above, the three scenarios of future fibre supply from nonwood sources can be defined as follows.

1. No change in current trends in nonwood pulping capacity
2. Trends in nonwood pulping capacity will increase by 10% over the current trend, from the year 1980 to the year 2050
3. Trends in nonwood pulping capacity will decrease by 10% beneath the current trend, from the year 1980 to the year 2050

An overall assumption that comes into play is that nonwood pulping capacity never reaches 0, but instead remains at about 10% of the initial capacity recorded in 1980.

Model outcomes

Two patterns of future nonwood fibre supply could be discerned from the model outputs. In some countries, the trend in nonwood capacity is rising. In Figure 5.6, future nonwood fibre supply is shown to rise at an exponential rate. This reflects the current trend in India and in other similar countries where traditional woody fibre supply is limited, and where breakthroughs in nonwood pulping technology such as high pressure and temperature pulping have made previously uneconomical fibre sources feasible and attractive to industry investment.

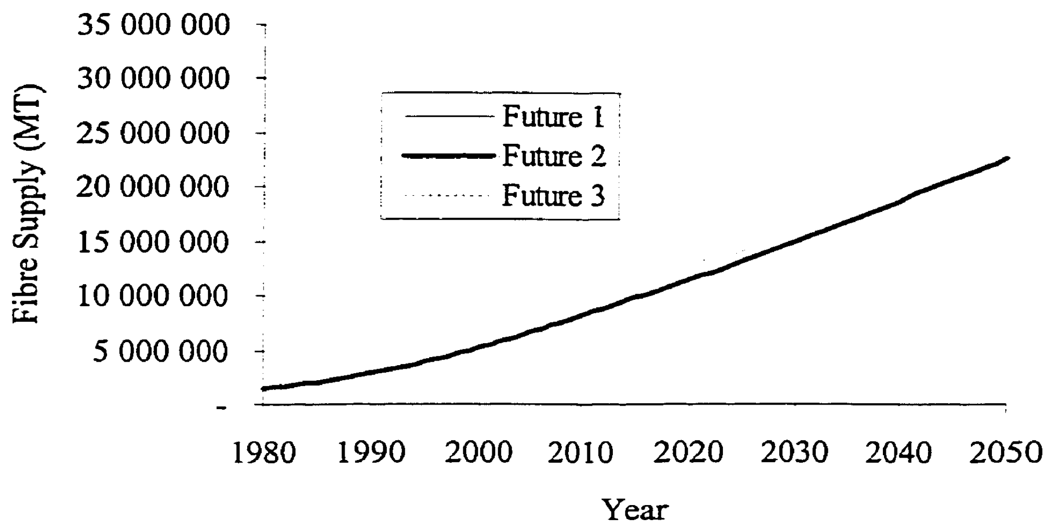


Figure 5.6 Projected fibre supply from nonwood sources, India (1980 - 2050)

In other countries, the opposite trend is shown, with the use of nonwood fibre becoming insignificant as old mills are taken offline and as new sources of woody fibres become available for the pulp and paper industry. This trend is illustrated in Figure 5.7.

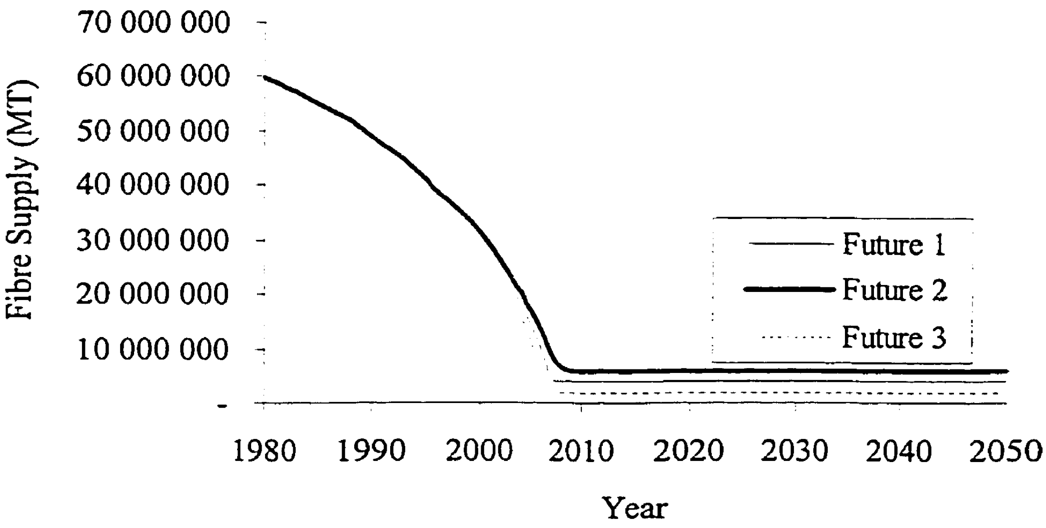


Figure 5.7 Projected fibre supply from nonwood sources, PR China (1980 - 2050)

China is an example of a country that once utilized a great deal of nonwood fibre, but which is now losing capacity without any indication of a future reversal of this trend. The difficulties associated with using nonwoods, such as the high silica content and variable fibre lengths, make wood a more attractive material for pulping. The establishment of successful plantations in parts of China has also reduced the need to rely heavily on nonwood fibres.

5.4.5 Total Population

Equation of total population

The fourth discrete variable encountered in the overall model is *f* (TP), or the function describing total population of a nation. The data presented in this section closely approximates some of the recent projections made by the United Nations Population Division Statistics (Population Division of the United Nations Secretariat 1999). The function for total population is shown as Equation 5.8.

Equation 5.8

$$TP = m_1 \cdot x + m_2 \cdot x^2 + m_3 \cdot x^3 + C$$

where
TP = Total population (#)
$m_1 - m_3$ = Coefficients corresponding to date
x = Year
C = Constant

In this equation, the number of coefficients used depends on the initial regression test conducted on the historical dataset. If the dataset corresponds better to a linear trend, the dataset utilizes a linear equation with a single coefficient. Conversely, if the dataset corresponds to a second- or third-degree polynomial trend, then the model activates the second and third coefficients. This allows exponential curves to be projected as well as flat trends.

Future definitions

Three scenarios of future total population can be defined as follows.

1. No change in current trends in total population growth
2. The rising trends in total population growth will increase by 10% over the current trend, from the year 1995 to the year 2050.
3. The rising trends in total population will decrease by 10% beneath the current trend, from the year 1995 to the year 2050

An overall assumption that comes into play is that negative trends of population growth will gradually approach the steady state, rather than decreasing to zero.

Model outcomes

The most typical outcome of the population model was of rising populations. The overall global trend predicted by the model is shown in Figure 5.8. It can be seen that population is predicted to rise by 100% over its current level. Should current trends be followed, as in Future 1, the global population will reach 10 billion around the year 2050. A 10% increase over the current trend would add an additional billion, while a 10% decrease would reduce the curve by almost as much. As stated before, these predictions are very close to global outlook scenarios developed by the United Nations Population Division Statistics (Population Division of the United Nations Secretariat 1999).

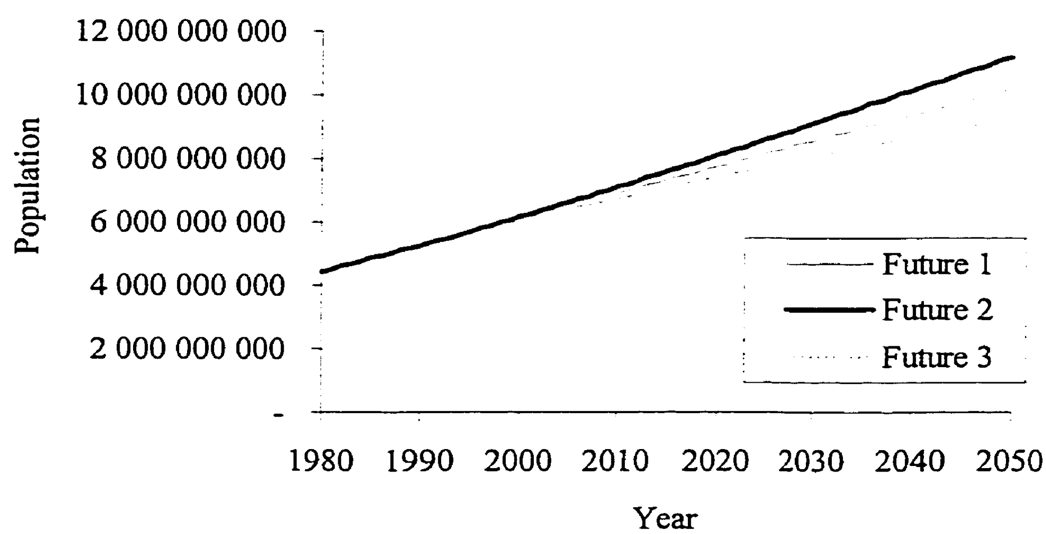


Figure 5.8 Projected world population, 1980 - 2050

In certain countries, the current trend is one of decline. For instance, Bosnia and Herzegovina has decreased in population drastically over the past 10 years. This decrease is related to unusual internal social pressure, in the form of a civil war, and is expected to slow. In the case of a negative population trend, the curves were modified to reflect a slow adjustment from decline to steady state, and eventually to increase. The modification is carried out by the formula described by Equation 5.9.

Equation 5.9

$$\int_{x_0}^{x} r \cdot PT^{(x-x_o)} dPT = PT_{LL}$$

where
x = Model year x
x_o = Most recent data reference point (year)
PT = Total population in model year x (#)
r = reducing factor
PT_{LL} = Lower limit of total population (# based on national population trends)

In this equation, all the factors are known except for *r*, which is the reducing factor appropriate for any given curve. In order to solve this equation, it is necessary to take its derivative as shown in the equation below.

Equation 5.10

$$\left[\left(\frac{1}{\ln(PT)}\right) \cdot r \cdot PT^{(x-x_0)} + C\right] - \left[\left(\frac{1}{\ln(PT)}\right) \cdot r \cdot PT^{(x_0-x_0)} + C\right] = PT_{LL}$$

where C is a constant.

Simplifying this, we can rewrite Equation 5.10 as shown below.

Equation 5.11

$$\left(\frac{r}{\ln(PT)}\right) \cdot \left(PT^{(x-x_0)} - 1\right) = PT_{LL}$$

Equation 5.11 has many solutions, but only one is appropriate for the portion of the curve under consideration. The equation can be solved for *r* using an iterative process.

In Figure 5.9, the modified population trends for Bosnia and Herzegovina are shown.

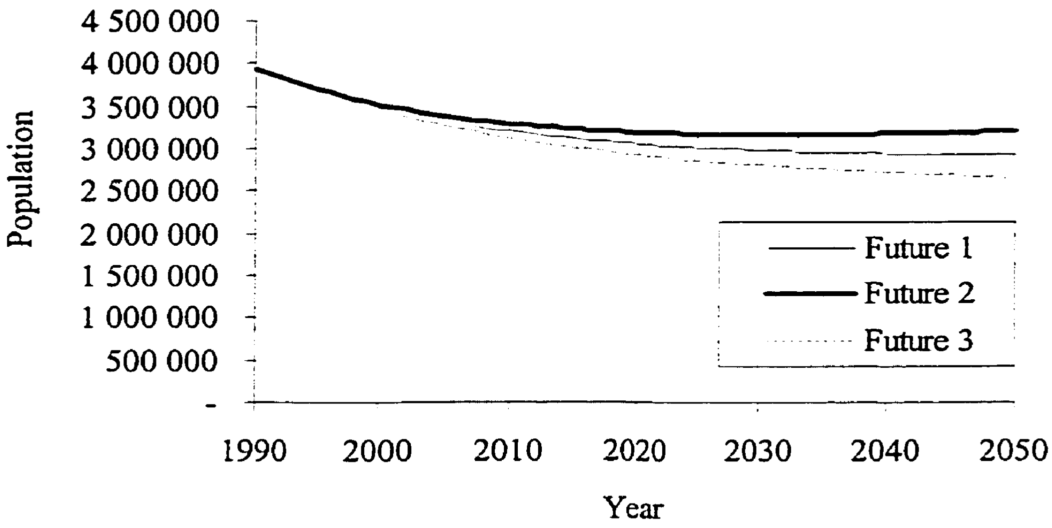


Figure 5.9 Projected population, Bosnia and Herzegovina (1990 - 2050)

5.4.6 Population Density

Equation of population density

The fifth discrete variable encountered in the overall model is *f* (DP), or the function describing population density within a nation. Density is modeled by considering the urban component of national population. The projected data presented in this section closely approximates some of the recent projections made by the United Nations Population Division Statistics (Population Division of the United Nations Secretariat 2000b, Population Division of the United Nations Secretariat 1999). The equation of population density can be described as follows.

Equation 5.12 $$DP = m_1 \cdot x + m_2 \cdot x^2 + C$$

where
DP = Urban population fraction (%)
$m_1 - m_2$ = Coefficients corresponding to date
x = Year
C = Constant

In this equation, the number of coefficients used depends on the initial regression test conducted on the historical dataset. If the dataset corresponds better to a linear trend, the dataset utilizes a linear equation with a single coefficient. Conversely, if the dataset corresponds to a second-degree polynomial trend, then the model activates the second coefficient. As a maximum of ten data points could be collected between 1980 and 2000, third-degree polynomial trends could not be calculated with any degree of confidence.

Assumptions

In the calculation of future trends in population density, three principal assumptions were made. They were:

1. That fractions of urban population and rural population are complementary and total 100% of the population of a given nation;
2. That current trends in urban or rural population density in any given country would not rise above 85% of the national population, describing an upper limit labeled DP_{UL}, and;
3. That current trends urban or rural population density in any given country would not fall beneath 15% of the national population, describing a lower limit labeled DP_{LL}.

If population density in a nation was initially higher than the set upper limit of 90% and described a rising trend, the assumption was modified as shown in Equation 5.13.

Equation 5.13 $$DP_{UL} = \left[\tfrac{1}{2} \cdot (100 - DP_{UL})\right] + DP_{UL}$$

where
DP_{UL} = Upper limit of urban population (%)

If urban population density was initially lower than 10% and characterized by a declining trend, the assumption was modified as shown in Equation 5.14 until the actual urban population component rate, as reported in the last available year of data, was higher than the lower limit provided by the equation.

Equation 5.14 $$DP_{LL} = DP_{LL} - \left[\tfrac{1}{2} \cdot (100 - DP_{LL})\right]$$

where
DP_{LL} = Lower limit of urban population (%)

In most cases, the urban population trends have been found to be dynamic but within the bounds of the set upper and lower limits. In many cases, the trend will cross these limits within the 50-year model horizon. In these cases, Equation 5.15 is used to calculate the tails of the equation from the last referenced data point until the year 2050. Note that this equation derived in the same way as Equation 5.11.

Equation 5.15 $$\left(\frac{r}{\ln(DP)}\right)\cdot\left(DP^{(x-x_0)}-1\right)=100-DP_L$$

where
x = Model year x
x_o = Most recent data reference point (year)
DP = Urban population component in model year x (%)
r = modifying factor
DP_L = Limit (upper or lower) of urban population (%)

Future definitions

Based on the equations given above, the three scenarios of future urban population can be defined as follows.

1. No change in current trends in urban and rural population development.
2. Trends in urban population growth will increase by 10% over the current trend, from the year 1995 to the year 2050, while rural population trends will decline by the same amount.
3. Trends in urban population growth will decrease by 10% beneath the current trend, from the year 1995 to the year 2050, while rural population trends will increase by the same amount.

Model outcomes

Two distinct patterns of urban and rural population development could be discerned from the model output. In the first, urban population experiences a gentle but increasing growth, balanced by a reduction in the rural population component. This is typified in Figure 5.10, which shows changes in the Canadian population.

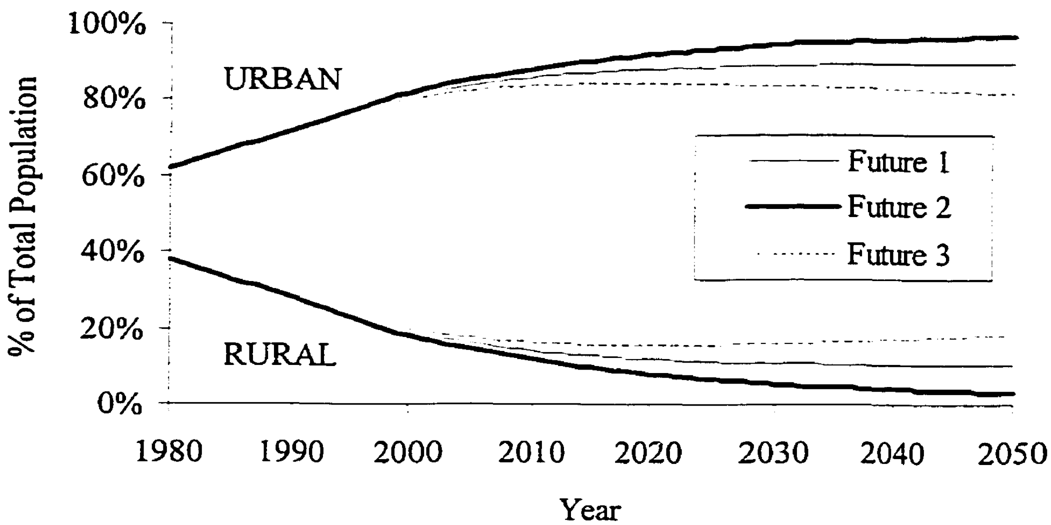


Figure 5.10 Trends in population density, Canada (1980 - 2050)

Some criticism may be raised of the Canadian example, since increases in population density in this country in the last decade may have much to do with the creation of municipalities with large areas incorporating both urban and rural land. The fact that rural land is incorporated into a municipal government framework, however, means that services provided might approach those of the urban landscape. This in turn might increase the possibilities for paper consumption and recycling.

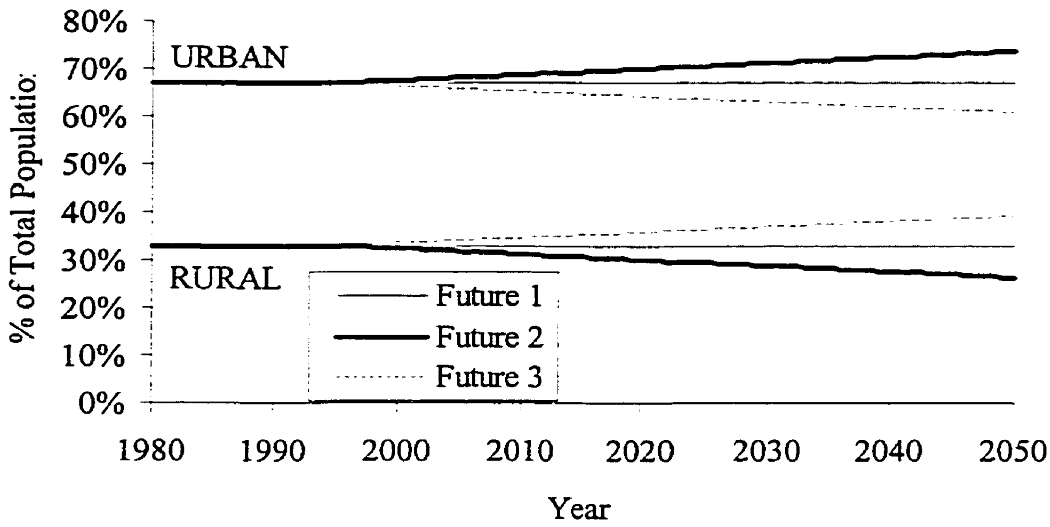


Figure 5.11 Trends in population density, Italy (1980 - 2050)

The second major trend displayed by population density is a static line, indicating very little shift between rural and urban population components. In countries such as Italy, the urban population density has remained stable for years and can be raised up and down through future scenarios, as illustrated in Figure 5.11.

5.4.7 Literate Population

Equation of literacy rate

The sixth and final discrete variable encountered in the overall model is f (LP), or the function describing literate population within a nation, taken as a percentage. The projected data presented in this section closely approximates some of the recent projections made by the United Nations Educational, Scientific and Cultural Organization (UNESCO Institute for Statistics 1999). The equation of literacy can be described as follows.

Equation 5.16 $$f(LP) = m_1 \cdot x + C$$

where
LP = Literate population fraction (%)
m_1 = Coefficient corresponding to date
x = Year
C = Constant

In this equation, only a linear trend could be estimated due to the limited amount of data available.

Assumptions

In the calculation of future trends in literacy, three principal assumptions were made. They were:

1. That literacy rates in most developed countries approaches 100%;
2. That literacy rates in any given country would not rise above 98% of the national population, providing an upper limit labeled LP_{UL}, and;
3. That literacy rates in any given country would not fall beneath 15% of the national population, describing a lower limit labeled LP_{LL}.

If literacy rates were initially higher than the set upper limit of 98% and described a rising trend, the assumption was modified as shown in Equation 5.17.

Equation 5.17 $$LP_{UL} = \left[\tfrac{1}{2} \cdot (100 - LP_{UL})\right] + LP_{UL}$$

where
LP_{UL} = Upper limit of literate population (%)

If literacy rates were initially lower than 15% and still falling, the assumption was modified as shown in Equation 5.18 until the actual literacy rate, as reported in the last available year of data, was higher than the lower limit provided by the equation.

Equation 5.18 $$LP_{LL} = LP_{LL} - \left[\tfrac{1}{2} \cdot (100 - LP_{LL})\right]$$

where
LP_{LL} = Lower limit of literate population (%)

In most cases, the literacy trends have been found to be dynamic but within the bounds of the set upper and lower limits. In many cases, the trend will cross these limits within the 50-year model horizon. In these cases, Equation 5.19 is used to calculate the tails of the equation from the last referenced data point until the year 2050. Note that this equation is derived in the same way as Equation 5.11.

Equation 5.19 $$\left(\frac{r}{\ln(LP)}\right)\cdot\left(LP^{(x-x_0)}-1\right)=100-LP_{UL}$$

where
x = Model year
x_0 = Most recent data reference point (year)
LP = Literate population in model year (%)
r = reducing factor
LP_{UL} = Upper limit of literate population (%)

Model outcomes

Literacy rates were found to follow three distinct patterns in the forecasting exercise. The first common pattern was one of rising literacy rates, as shown in Figure 5.12.

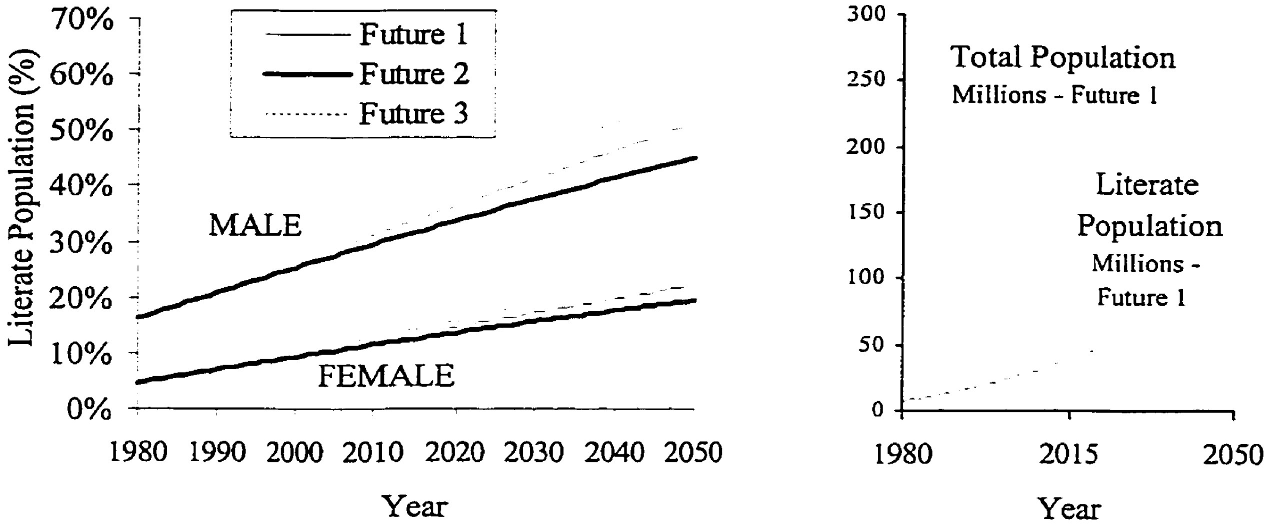


Figure 5.12 Trends in literacy rates (left) and total population (right), Nigeria (1980 - 2050)

The predicted literacy rates for Nigeria are shown. As is common in many developing countries, male literacy is much higher than female literacy. The trend displayed is similar for both genders, with female literacy rising at only a slightly lower rate than male literacy. In the case of Nigeria, literacy rates more than double within the 50-year forecasting horizon.

While the literacy rates follow a fairly linear distribution, it is interesting to note that the rise in population associated with this particular country means that the gain in actual literate population follows an exponential distribution. This is shown clearly on the right side of the graph, where literate population is exponentially growing in comparison to the total population.

Two other distinct patterns could be seen in projections of literacy rates. In one pattern, literacy rises at a very low rate. When adjusted according to Future Scenario 2, the result is a change from a net positive trend in adult literacy to a negative trend. This is illustrated by the example shown in Figure 5.13.

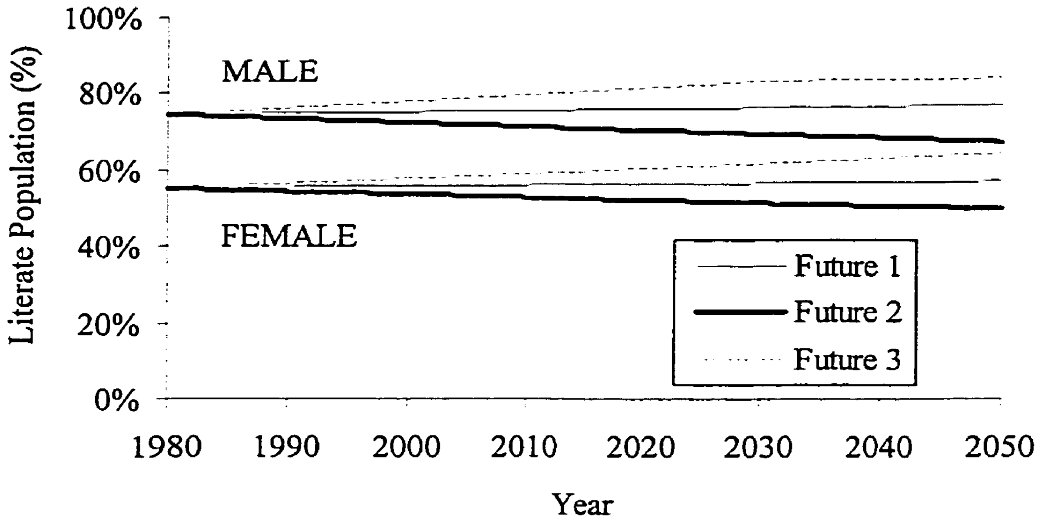


Figure 5.13 Trends in literacy rates, Saudi Arabia (1980 - 2050)

The other distinct pattern evident in the forecasts was related to countries where literacy already approaches 100% of the total adult population, and the current trend is stable. In these cases, literacy cannot be adjusted above or below the current trend. Developed countries, where literacy rates are very stable and no change is anticipated in the foreseeable future, often display the resulting flat projection.

5.5 Model synthesis

5.5.1 Combination and analysis of input and output variables

Having identified the equations for each of the model factors and projected these factors from the baseline year of 1995 until the planning horizon of 2050, it is possible to combine all of these factors into the equation first hypothesized in Equation 5.1. By taking the historical trend lines associated with each of the discrete factors and regressing them against the historical data for paper production, consumption, and recycling, the overall equation can be derived. The stages of the model synthesis consisted of the following.

1. In order to determine which factors are relevant for which country, the historical datasets for input and output variables were compared to each other using a stepwise regression. In a stepwise regression, the historical datasets attached to each of the discrete input variables was analyzed against each of the three output variables. This was done in order to exclude those variables that either have no predictive ability within the country at hand, or those variables that are highly correlated with other predictor variables. A stepwise regression can also reduce the risk of multicollinearity that is present in normal regression analysis (Kvanli 1988). One new variable was added at each stage of the analysis. The resulting partial F values for all variables were examined to determine the degree to which each variable contributed to the revised overall equation. In order for variables to be included in the model, their inclusion had to increase the r^2 value at a significance level of 0.1. In order for variables already included in the model to be considered superfluous and removed upon the addition of a new variable, their presence had to decrease the r^2 value of the model at a significance level of 0.15.

2. Upon completion, the stepwise regression essentially provided a list of the input variables that demonstrated high correlation with each of the three output variables (paper production, consumption, and recycling) in turn, for each of the 230 nations initially included in the model.

3. For each of the three output variables, a unique regression equation was compiled using only those input variables found to demonstrate high correlations in the relevant country.

A simple regression was carried out on each of these equations to determine the unique coefficients associated with to each country.

4. Using the projected datasets of each input variable in conjunction with the regression coefficients calculated for each of the output variables, future projections of paper production, paper consumption, and wastepaper recycling were created from the baseline year of 1980 to the final year of 2050.

The analysis was carried out using the SAS System for Windows version 7.0.

5.5.2 Distribution of significant input variables

From the stepwise regression, the significant input variables were identified for each of the countries in which significant correlations could be found. From the point of view of model validation, it is interesting to see if there is a pattern to the distribution of these controlling input variables.

The distribution of significant input variables is listed in full in Appendices 1-3, for production, consumption, and recycling respectively. Note that the highlighted entries correspond to those countries where the correlation was considered acceptable.

The geographic distribution of each of the six discrete input variables for paper production is shown on the next page. From Figure 5.14, it can be seen that the countries that share common, statistically significant input factors, are clumped into discrete geographic regions. For instance, Map A indicates those countries in which fibre available from disturbed and undisturbed forests contributes significantly to one of the three output models. These countries are concentrated in Europe, North America, and South America. In North and South America, most nations control large forest areas and produce a large quantity of paper. In Europe, both forest areas and paper production levels are lower. Even within Europe, however, much of the supply for pulpwood is still grown domestically, particularly in Scandinavia and Western Europe (PPI 2000a, PPI 2000b, PPI 1996).

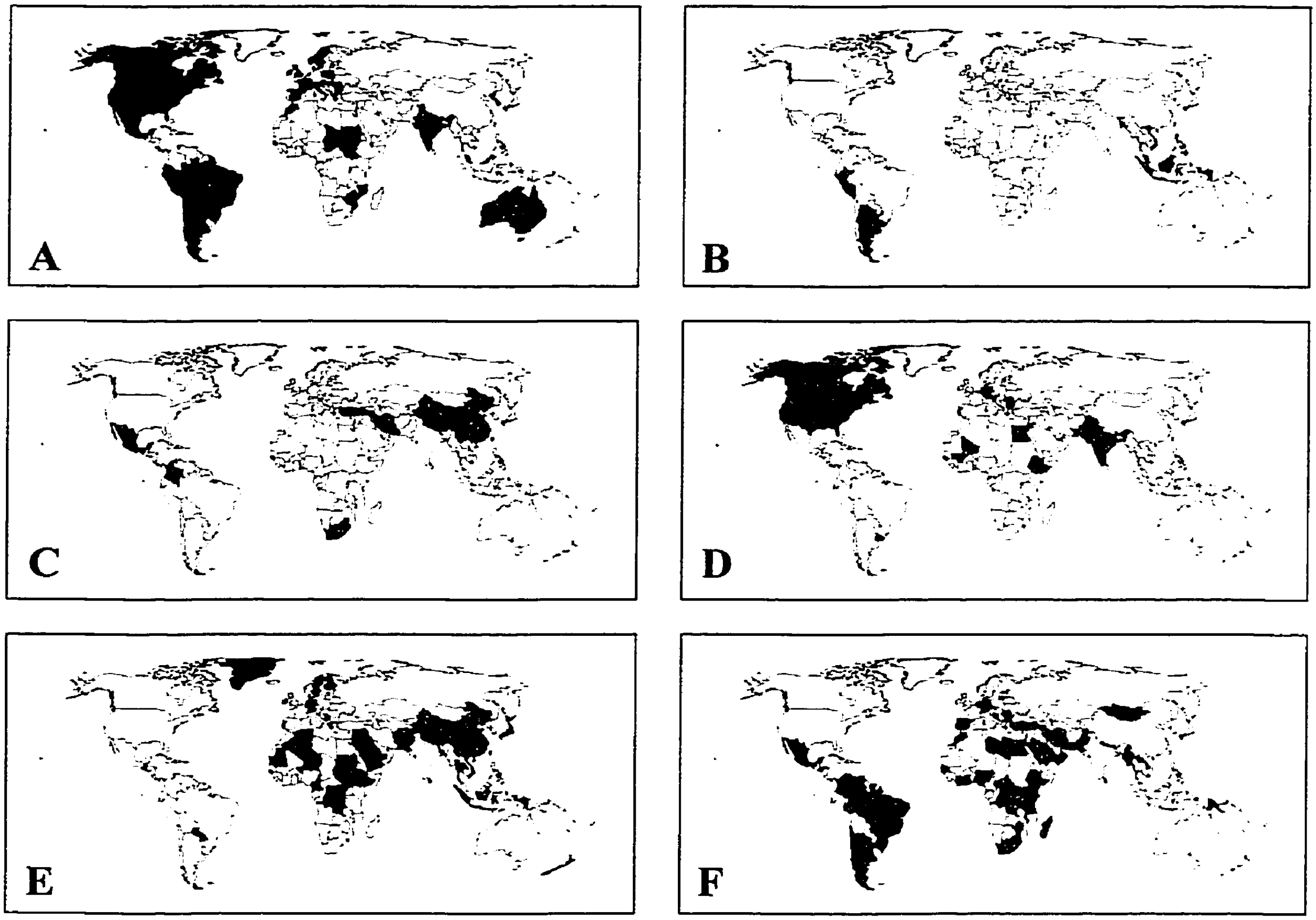


Figure 5.14 Global distribution - statistically significant input variables, paper production.

A:	**Undisturbed and disturbed forest fibre supply**
B:	**Industrial plantations**
C:	**Nonwood fibre supply**
D:	**Total population**
E:	**Population density**
F:	**Literate population**

Map B indicates those countries for which plantations are a controlling factor in paper production. Not surprisingly, these countries are grouped into parts of East Asia and South America. These are geographic regions that have been found to be ideal for the establishment and propagation of plantation species. Note that some other countries, which might be expected to relate closely to plantation establishment, do not include plantation fibre supply as a controlling factor. For instance, India has large plantation areas and one might expect plantation fibre supply to be a controlling factor in paper production. In the case of India, however, the correlation between population and paper production proved to be strong enough to force the removal of plantations from the model.

Map C indicates those countries for which nonwood fibre supply correlates strongly to paper production. With one exception, these countries are clustered around the equator, where year-round growing seasons and a dry climate provides an impetus for the use of nonwoods. In China, the use of nonwood fibre supply is declining rapidly, and this has perpetuated a loss in overall fibre capacity. This in turn has resulted in a strong correlation between nonwood fibre supply and paper production (PPI 1997).

Map D indicates countries in which trends in total population can be closely related to trends in paper production. These countries seem to fall into one of two criteria: those countries where populations are fairly stable or growing slowly, and where the paper industry has matured, and those countries where population is rising significantly, and where the paper industry is still developing. The countries of North America fall into the former category, while India and parts of Africa can be grouped into the latter.

Map E indicates those countries where population density can be related to paper production. With a few exceptions, these countries are grouped in Africa and Asia, and reflect the correlation between rising urban populations and a developing paper industry. The population densities of Germany, Sweden and Finland can also be related to paper production. Closer examination of these countries will show that trends in both paper production and population density are rising slowly, and show signs of being collinear.

Map F indicates those countries where changes in literacy rates can be related to paper production. Note that almost every country where literacy was found to be significant is found in South America, Africa, or in Asia. In these regions of the world, literacy is found to be rising significantly as educational programs are established. This rise in literacy is a mark of the developing nature of these countries, and it is no surprise that rising trends in paper production may be related to this phenomena.

5.6 Model validation

Model validation took place in several stages. At each stage of data manipulation, checks were included in the system in order to ensure that no country was included in the model without a statistically valid relationship between the input and output data. These relationships were tested within each of the discrete input variable functions, as well as during the model development for each of the three output variables.

In the end, the ability of the model to account for significant portions of global paper and paperboard production, consumption, and wastepaper recycling was also analyzed to determine the validity of applying this model on a global scale.

5.6.1 Testing for correlation

Stepwise regression

One of the parameters set in the stepwise regression analysis was that no variable could be added to the overall equation unless its inclusion resulted in an increase of the total r^2-value at a significance level of 0.1. This ensured the all variables included in the model were significantly correlated to the dataset in question.

For the 230 countries initially included in the model, the following results were found.

- In 93 countries, at least one of the six discrete input variables displayed significant correlation with paper and paperboard production;
- In 162 countries, at least one of the six discrete input variables displayed significant correlation with paper and paperboard consumption, and;
- In 79 countries, at least one of the six discrete input variables displayed significant correlation with wastepaper recycling.

Thus, after the stepwise regression was complete, the modeling exercise continued using the 93, 162, and 79 countries identified with each of the three output variables respectively.

Non-linear regression

After each non-linear equation was created using the countries and variables identified during the solved, the correlation that the calculated trend had with historical data was determined. A minimum r^2-value was set at 0.85. If an equation displayed a lower correlation value than the minimum r^2-value, it was considered to be inaccurate and that country was removed from the global model. In this way, many countries were screened from the model output.

Of the countries analyzed through non-linear regression, the following results were found.

- Of 93 countries analyzed in relation to paper and paperboard production, 55 (59%) were found to have positive correlations with r^2-values exceeding 0.85;
- Of 162 countries analyzed in relation to paper and paperboard consumption, 65 (40%) were found to have positive correlations with r^2-values exceeding 0.85, and;
- Of 79 countries analyzed in relation to wastepaper recycling, 38 (48%) were found to have positive correlations with r^2-values exceeding 0.85.

5.6.2 Testing for global scope

In order to verify that the model can accurately represent global trends in production, consumption, and recycling, it is important to know the extent to which the model represents the total outputs in these areas. The desired goal is the development of models that can describe more than 80% of global totals for each of the three defined output variables.

The three models were each found to be valid in a select number of countries. The relevant production, consumption, and recycling statistics were summarized for these countries, as shown in Table 5.1, Table 5.2, and Table 5.3. These sums were compared to the global totals for each of the three commodities, and the fraction of global output that the models described was calculated.

It was found that the model for paper and paperboard production, which was valid in 55 countries, accounted for 94% of the global production in the baseline year of 1995. This means that only 6% of worldwide production was not accounted for by the model.

The model for paper and paperboard consumption was less successful, but still accounted for 81% of the global consumption of these products in the baseline year of 1995. Interestingly, the consumption model was valid in 65 countries, which is more than either of the other two models. The lower scope of this model, however, indicates that consumption of paper is not limited to a select group of countries, but rather is spread across a very large number of countries. It also indicates that the variables chosen for the model do not explain all the variation in actual paper consumption.

The model for wastepaper recycling was very successful, accounting for 96% of total global recycling in 1995. The model was only valid in 38 countries, which is an indication of the limited number of countries that have invested in recycling technology. Admittedly, this could result in the model becoming less accurate as it approaches the forecasting horizon, as the number of countries that utilize recycling will probably increase within the next 50 years.

Table 5.1 Paper and paperboard production (1995) for countries included in the model

Country	r-square value	Paper & paperboard production (MT)	Country	r-square value	Paper & paperboard production (MT)
Albania	0.95	35 250	Netherlands	0.96	2 967 000
Argentina	0.85	1 019 000	North Korea	0.86	70 000
Australia	0.88	2 259 000	Norway	0.90	2 263 000
Austria	0.99	3 599 000	Pakistan	0.98	329 500
Bangladesh	0.95	164 000	Philippines	0.87	613 000
Brazil	0.95	5 856 000	Portugal	0.92	977 000
Bulgaria	0.89	178 250	Romania	0.90	362 000
Canada	0.91	18 698 000	Saudi Arabia	0.85	13 000
China	0.99	24 000 000	South Africa	0.85	1 936 500
Colombia	0.96	689 000	South Korea	0.99	6 877 500
Costa Rica	0.85	30 000	Spain	0.94	3 684 000
Cuba	0.85	49 000	Sudan	0.89	2 500
Egypt	0.86	221 000	Swaziland	0.94	60 000
Estonia	0.96	21 850	Sweden	0.96	9 169 000
Finland	0.96	10 942 000	Switzerland	0.96	1 442 000
France	0.99	8 617 000	Taiwan	0.99	4 243 000
Germany	0.85	14 827 000	Tanzania, United Republic	0.83	27 000
Greece	0.92	568 500	Thailand	0.99	1 953 500
Hong Kong	0.85	280 000	Tunisia	0.96	90 000
Hungary	0.85	321 000	Turkey	0.90	1 235 000
India	0.99	3 025 000	Uganda	0.91	3 000
Indonesia	0.99	3 654 500	United Kingdom	0.98	6 095 000
Israel	0.95	261 000	United States of America	0.97	85 144 000
Italy	0.96	6 802 000	Uruguay	0.97	87 000
Jordan	0.87	23 000	Viet Nam	0.93	125 000
Latvia	0.98	6 500	Yugoslavia SFR	0.92	10 000
Malaysia	0.95	648 000	Zimbabwe	0.92	84 000
Mexico	0.87	3 047 000			

TOTAL (Accepted Countries): 269 367 850 MT
TOTAL (Global): 286 350 970 MT
Model scope: 94% of total global production

Table 5.2 Paper and paperboard consumption (1995) for countries included in the model

Country	r-square value	Paper & paperboard consumption (MT)	Country	r-square value	Paper & paperboard consumption (MT)
Albania	0.95	38 695	Mexico	0.91	3 991 717
Australia	0.88	3 840 850	Micronesia	0.90	91
Austria	0.92	7 164 550	Netherlands	0.93	7 513 500
Bahamas	0.96	8 500	New Zealand	0.88	724 450
Bangladesh	0.96	440 000	Norway	0.92	4 656 550
Belgium-Luxembourg	0.91	4 745 200	Pakistan	0.92	520 100
Bosnia and Herzegovina	0.94	156	Palau	0.93	95
Bulgaria	0.95	255 231	Paraguay	0.94	69 160
Canada	0.85	34 013 000	Philippines	0.91	911 850
Chile	0.97	909 350	Portugal	0.91	1 970 050
China	0.99	26 759 350	Romania	0.96	558 850
Christmas Island	0.85	44	Saint Helena	0.85	127
Cocos Island	0.94	269	Saint Kitts & Nevis	0.86	205
Colombia	0.92	1 022 008	Singapore	0.87	1 138 550
Costa Rica	0.85	360 150	Spain	0.97	6 767 200
Cuba	0.92	58 711	South Korea	0.99	8 568 350
Czech Republic	0.90	1 268 500	Suriname	0.90	2 100
Denmark	0.94	1 597 250	Swaziland	0.92	58 500
Ecuador	0.86	426 600	Switzerland	0.90	3 274 500
Faeroe Islands	0.85	2 008	Taiwan	0.99	5 992 450
France	0.95	16 580 500	Thailand	0.98	2 712 900
Guatemala	0.88	180 535	Tunisia	0.96	182 055
India	0.98	3 446 747	Turkey	0.92	1 866 400
Indonesia	0.99	4 647 897	Tuvalu	0.85	3
Iran	0.94	730 383	United Arab Emirates	0.85	281 630
Ireland	0.89	440 900	United Kingdom	0.94	13 538 500
Israel	0.96	639 100	United States of America	0.94	106 295 500
Italy	0.98	11 961 500	Uruguay	0.85	127 981
Japan	0.94	32 002 450	Viet Nam	0.93	160 033
Jordan	0.91	108 850	Wake Island	0.85	43
Lithuania	0.96	77 600	Wallis and Futuna Islands	0.85	16
Malaysia	0.97	2 053 950	Yugoslavia (SFR)	0.92	10 000
Mauritius	0.95	30 602			

TOTAL (Accepted Countries): 332 034 694 MT
TOTAL (Global): 409 278 516 MT
Model scope: 81% of total global consumption

Table 5.3 Wastepaper recycling (1995) for countries included in the model

Country	r-square value	Wastepaper recycling (MT)	Country	r-square value	Wastepaper recycling (MT)
Albania	0.85	3 000	Mauritius	0.85	3 000
Australia	0.95	1 138 500	Mongolia	0.88	3 000
Austria	0.90	972 000	Netherlands	0.98	2 177 500
Belgium-Luxembourg	0.93	686 000	North Korea	0.87	6 500
Brazil	0.85	1 501 500	Norway	0.96	262 000
Canada	0.96	2 694 000	Poland	0.91	225 000
China	0.98	8 246 000	Saudi Arabia	0.88	37 500
Denmark	0.97	500 500	South Africa	0.93	590 000
Ecuador	0.88	71 000	South Korea	0.99	3 256 000
Finland	0.94	492 000	Spain	0.96	2 117 000
France	0.93	3 701 000	Sweden	0.88	1 253 500
Germany	1.00	10 531 000	Switzerland	0.95	900 500
Greece	0.86	232 500	Taiwan	0.94	2 607 000
Iran	0.85	90 000	Thailand	0.86	553 500
Israel	0.90	137 000	United Kingdom	0.90	3 828 000
Japan	0.97	15 157 000	United States of America	1.00	35 749 000
Lebanon	0.87	7 500	Venezuela	0.85	272 500
Macau	0.88	27 000	Viet Nam	0.88	86 000
Malaysia	0.83	263 500	Zimbabwe	0.91	26 500

TOTAL (Accepted Countries): 100 405 000 MT
TOTAL (Global): 104 544 000 MT
Model scope: 96% of total global recycling

5.7 Conclusions

The principal conclusions that can be drawn from this section of work are as follows.

1. The choice to utilize various social and physical factors in the modeling exercise were supported by the geographic distribution of countries where each factor was statistically significant. Literacy rates and population density, for instance, were most prominently recognized as correlating factors in Africa, Asia and South America, where the number of developing nations currently undergoing rapid social change is very high. Fibre supply from forests, plantations, and nonwoods could be related to countries where these sources of supply are in abundance.

2. The use of social factors (population, population density, and literacy rate) in combination with physical factors (forest fibre supply, plantation fibre supply, and nonwood fibre supply) can result in effective modeling of paper and paperboard production. The model was statistically sound in 55 countries and explained 94% of total world paper production in the baseline year (1995). Potential problems for future forecasting are related to the countries that were not incorporated into the model. Due to poor correlations or bad data, the model eliminated countries that are currently or may become dominant forces in the supply of pulp or paper products, such as New Zealand and Russia.

3. The use of social and physical factors can also result in the effective modeling of wastepaper recycling. The model was found to be statistically sound in 38 countries, and explained 96% of the total world wastepaper recycling in the baseline year (1995). The principal concern for future error in the projection of wastepaper recycling is tied to the fact that only countries seriously involved in wastepaper recycling during the baseline year are considered within the model. Countries that as of 1995 had not begun to recycle wastepaper to a significant extent could not successfully match the criteria set out in the model. Thus, any additional countries that enter the recycling market before the model horizon are not included in the forecast.

4. The use of social and physical factors does not result in the effective modeling of paper and paperboard consumption. While the model was statistically sound in 65 countries,

the model could only explain 81% of the global consumption of paper. This was 9% short of the arbitrary limit initially set for the model. The principal error was linked to the fact that consumption of all forest products is linked to imports and to economic factors that were not included in the model.

6 Implications of sludge disposal practices

6.1 Introduction

6.1.1 Abstract

Fundamental information about the chemistry of sludge, published rates of sludge generation, and models of paper production and wastepaper recycling were combined to create a predictive model. The goal of the modeling exercise was to determine and project global sludge production until the year 2050. It was predicted that a global shift in paper and paperboard production will result in the Asia-Pacific region emerging as a major producer of papermill sludge. Global production of papermill sludge will rise over the next 50 years by between 48 and 86% over current levels. Sludge was found to contain a large amount of woody organic material, but the proportion of this material in the sludge was found to drop as recycling programs were implemented. Sludge was also found to contain a large amount of woody carbon, which comprised about 30% of the total sludge solids. The presence of such a large proportion of woody carbon may become important if a system of carbon crediting is implemented for the forest industry.

6.1.2 Objectives

The principal goal of this section of study was to extrapolate global sludge production and describe the role that sludge plays in the carbon balance of the pulp and paper industry.

The specific objectives of this study are to:

1. Synthesize a model using fundamental data on sludge composition, published rates of sludge generation, and verified models of paper production and wastepaper recycling, that can identify trends in total sludge production, the woody organic component and the woody carbon component;
2. Forecast global sludge production to the model horizon of 2050, and identify geographic and absolute trends in papermill sludge production distributions;
3. Analyze the impact that paper production and wastepaper recycling trends have upon the woody organic and woody carbon components of sludge over time;

4. Discuss the implications of the organic and carbon contents of sludge, in relation to possible disposal problems and policy positions.

6.2 Model development

The development of a model to predict sludge production is based upon three existing datasets. The chemical characteristics of sludge, in terms of organic and carbon content, have been described in previous sections of this study. The generation rates associated with papermill sludge have been elucidated in the literature, and will be adapted for use within this model. Finally, the datasets derived from estimates of paper production and wastepaper recycling developed in the previous chapter will be incorporated.

6.2.1 Sludge characteristics

The sludge parameters used in the model combined the physical and chemical characteristics determined earlier in this study, and the generation rates and proportions gleaned from the literature in order to develop a model that can estimate sludge production in terms of total production, woody organic content, and organic carbon content.

In Table 6.1, a summary of the chemical characteristics used is presented. The information in this table was originally developed in Chapter 4, with supplementary information from the literature provided in Chapter 2 (Sjöström 1993).

Table 6.1 Chemical characteristics of the woody portion of sludge (% of total sludge solids)

	Cellulose[1]		**Lignin**[1]		**Extractives**[1]	
	Total	Carbon	Total	Carbon	Total	Carbon[2]
Category I:	52.6 %	23.1 %	10.5 %	6.5 %	3.9 %	2.0 %
Category II:	44.7 %	19.7%	16.0 %	9.9 %	6.1 %	3.1 %
Category III:	33.5 %	14.7 %	18.4 %	11.4 %	3.1 %	1.6 %

[1]% of Total sludge solids, based on oven dry mass
[2]Estimated values based on a random sampling of extractive structures

The three categories of mills described in the table above were found to be statistically significant in Chapter 4. By utilizing different categories of mills, the level of resolution that can be attained by the model of sludge production will be increased.

6.2.2 Sludge generation rates by mill category

The sludge generation rates used in this study are based on a report released by Ortech (Bellamy 1995). This report examined sludge production from a number of mills in Ontario. Papermill sludge generation rates were measured in terms of primary and secondary sludge. The specific mill operations, in terms of mechanical or chemical pulping process, were categorized and sludge generation was reported based on these operations. The generation rates are reproduced in the table below.

Table 6.2 Effluent characteristics and sludge generation rates for different processes

Mill type	BOD *(kg/MT)*	TSS *(kg/MT)*	Primary *(%)*	Secondary *(%)*	TOTAL *(%)*
Groundwood	0.9	1.9	7.0	1.8	8.8
Semi-chemical	2.0	2.4	2.0	1.9	3.9
Sulphite	10.5	16.0	5.0	2.8	7.8
Unbleached Kraft	1.6	2.6	2.5	0.7	3.2
Bleached Kraft	3.2	5.5	6.0	2.6	8.6
Non-integrated	2.4	2.5	4.0	0.7	4.7
Waste paper	0.32	0.9	4.0	0.7	4.7
Deinking	2.1	3.7	26.0	2.4	28.4

Sources: Bellamy 1995, Badar and Cutbirth 1993

In order to determine a single, national-level sludge generation rate, the pulp and paper producing capacities in each country were examined. Historical databases of paper production define capacity by the pulping operations, as shown in the Pulp and Paper International Annual Reviews (PPI 2000a, etc.) as well as in annual yearbooks published by the Food and Agriculture Organization of the United Nations (FAO 2000, etc.). These methods of paper production were incorporated into the model database, in order to utilize the full range of generation rates provided by the table above. Once paper production was organized by mill type, the generation rates reported in the literature could be applied. An overall sludge generation rate for each country within the model was determined by averaging generation rates across the full variety of mill types present in that country. This data is presented in Table 6.3.

The examination of historical data on mill types also allowed the sludge output for each country to be divided by the mill categories assigned in Chapter 4. This division allows the model to utilize the full range of sludge characteristics as described in Table 6.1. The division of mills by mill category is also presented in Table 6.3.

For all estimates of generation rates, 1995 was utilized as the baseline year.

Table 6.3 Estimates of sludge generation rates, by mill type and country

Country	Type I			Type II			Type III		
	Primary *(kg/MT)*	Secondary *(kg/MT)*	% *National*	Primary *(kg/MT)*	Secondary *(kg/MT)*	% *National*	Primary *(kg/MT)*	Secondary *(kg/MT)*	% *National*
Argentina	3.76	1.84	36.5%	4.0	0.7	45.9%	26.0	2.4	17.6%
Australia	5.06	1.93	38.7%	4.0	0.7	43.8%	26.0	2.4	17.5%
Austria	5.00	1.93	70.7%	4.0	0.7	19.3%	26.0	2.4	10.1%
Bangladesh	5.26	1.90	80.5%	4.0	0.7	11.8%	26.0	2.4	7.7%
Belgium	6.45	2.24	7.0%	4.0	0.7	85.4%	26.0	2.4	7.6%
Bosnia & Herzegovina	0.00	0.00	0.0%	4.0	0.7	100.0%	26.0	2.4	0.0%
Brazil	5.06	2.08	46.8%	4.0	0.7	48.3%	26.0	2.4	5.0%
Bulgaria	3.81	1.61	3.4%	4.0	0.7	96.6%	26.0	2.4	0.0%
Canada	6.15	2.13	82.9%	4.0	0.7	8.5%	26.0	2.4	8.5%
Chile	5.69	2.26	92.1%	4.0	0.7	3.9%	26.0	2.4	3.9%
China	0.72	0.37	57.4%	4.0	0.7	39.0%	26.0	2.4	3.5%
Colombia	2.21	0.99	42.8%	4.0	0.7	57.2%	26.0	2.4	0.0%
Cuba	4.50	1.96	43.8%	4.0	0.7	56.3%	26.0	2.4	0.0%
Czech Republic	4.82	2.05	45.7%	4.0	0.7	36.0%	26.0	2.4	18.3%
Denmark	2.00	1.90	0.0%	4.0	0.7	100.0%	26.0	2.4	0.0%
Egypt	4.50	1.96	6.1%	4.0	0.7	93.9%	26.0	2.4	0.0%
Estonia	2.50	0.70	62.8%	4.0	0.7	37.2%	26.0	2.4	0.0%
Finland	6.21	2.16	92.8%	4.0	0.7	3.6%	26.0	2.4	3.6%
France	5.40	2.03	46.4%	4.0	0.7	43.0%	26.0	2.4	10.6%
Germany	6.22	2.19	12.0%	4.0	0.7	75.9%	26.0	2.4	12.0%
Greece	4.50	1.96	13.0%	4.0	0.7	87.0%	26.0	2.4	0.0%
Hong Kong	0.00	0.00	0.0%	4.0	0.7	63.2%	26.0	2.4	36.8%
Hungary	4.50	1.96	32.6%	4.0	0.7	67.4%	26.0	2.4	0.0%
India	2.70	1.13	100.0%	4.0	0.7	0.0%	26.0	2.4	0.0%
Indonesia	4.50	1.96	74.1%	4.0	0.7	16.8%	26.0	2.4	9.1%
Israel	4.50	1.96	30.4%	4.0	0.7	69.6%	26.0	2.4	0.0%
Italy	5.19	1.45	56.9%	4.0	0.7	40.7%	26.0	2.4	2.5%
Japan	5.57	2.19	41.8%	4.0	0.7	46.5%	26.0	2.4	11.7%
Lithuania	7.00	1.80	17.1%	4.0	0.7	82.9%	26.0	2.4	0.0%
Malaysia	4.50	1.96	31.3%	4.0	0.7	68.3%	26.0	2.4	0.4%
Mexico	3.19	1.27	41.5%	4.0	0.7	49.2%	26.0	2.4	9.3%
Netherlands	4.50	1.96	29.4%	4.0	0.7	59.4%	26.0	2.4	11.2%
Norway	6.44	1.94	78.5%	4.0	0.7	10.8%	26.0	2.4	10.8%
Pakistan	5.70	2.66	81.1%	4.0	0.7	18.9%	26.0	2.4	0.0%
Philippines	2.90	0.90	64.2%	4.0	0.7	17.9%	26.0	2.4	17.9%
Portugal	5.29	2.25	93.2%	4.0	0.7	6.8%	26.0	2.4	0.0%
South Africa	4.08	1.54	65.9%	4.0	0.7	17.1%	26.0	2.4	17.1%
South Korea	6.40	2.28	46.3%	4.0	0.7	30.1%	26.0	2.4	23.6%
Spain	5.57	2.28	28.3%	4.0	0.7	66.5%	26.0	2.4	5.2%
Sweden	5.46	2.00	84.3%	4.0	0.7	7.8%	26.0	2.4	7.8%
Switzerland	5.84	2.38	27.1%	4.0	0.7	51.8%	26.0	2.4	21.1%
Taiwan	6.00	2.60	31.0%	4.0	0.7	66.9%	26.0	2.4	2.1%
Thailand	4.46	1.98	62.8%	4.0	0.7	32.2%	26.0	2.4	5.1%
Tunisia	4.50	1.96	46.9%	4.0	0.7	53.1%	26.0	2.4	0.0%
Turkey	3.52	1.29	43.1%	4.0	0.7	49.1%	26.0	2.4	7.7%
United Kingdom	6.36	1.81	20.0%	4.0	0.7	63.4%	26.0	2.4	16.5%
United States	5.52	2.52	49.8%	4.0	0.7	42.3%	26.0	2.4	7.9%
Viet Nam	4.70	2.28	43.4%	4.0	0.7	42.2%	26.0	2.4	14.3%
Yugoslavia	5.77	2.23	59.2%	4.0	0.7	24.3%	26.0	2.4	16.5%

6.2.3 Paper production and recycling

The third component of the sludge production model is the input required from the models developed in Chapter 5. For the purposes of this study, models of paper production and paper recycling will be utilized. The output from these models, based on the input variables and future scenarios defined in the previous chapter, are shown in Figure 6.1 below.

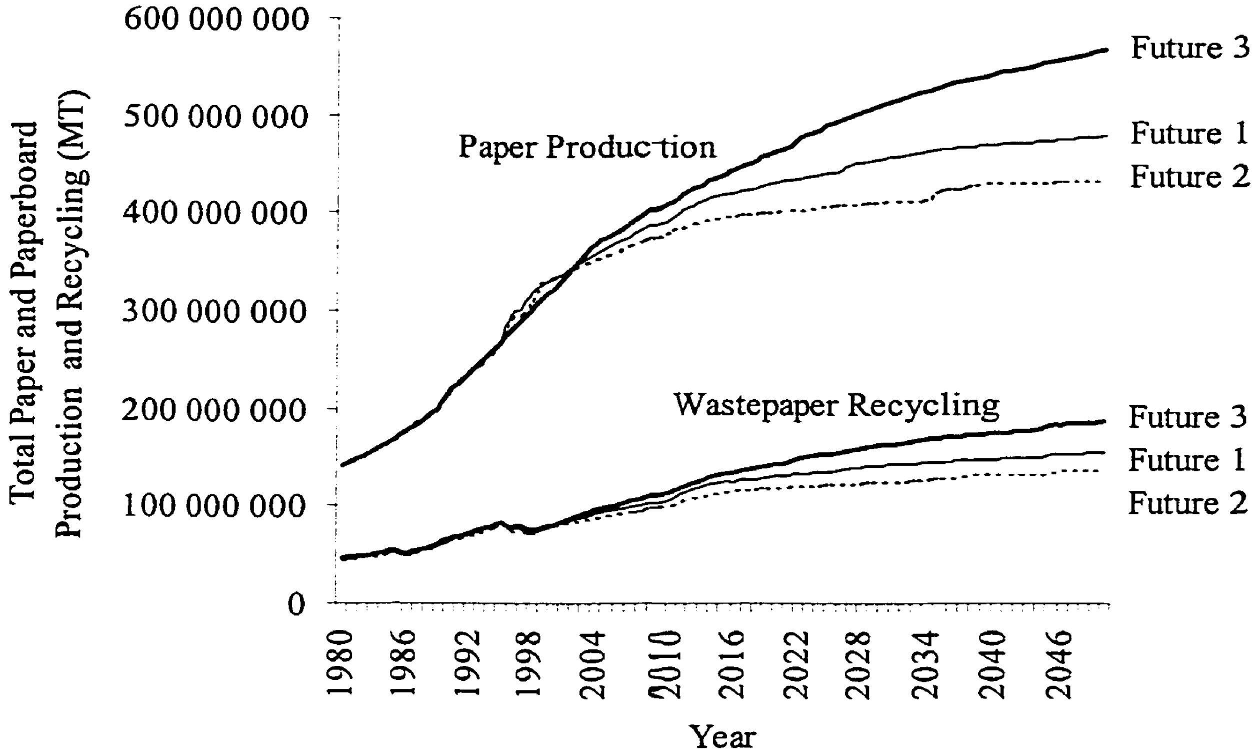


Figure 6.1 Projected Paper Production and Recycling (1980-2050)

The futures described in the figure above are the same as those described in Chapter 5. The paper production model and wastepaper recycling model are successful in describing above 90% of the global total in these two categories, in the base year of 1995.

Note that the curve for wastepaper recycling indicates the total level of recycled paper being produced, while the curve for paper production includes both recycled and virgin paper. The additional paper supply provided through increased recycling efforts in Future 3 is partially responsible for the extremely high curve of total paper production that is described for this scenario.

6.2.4 Development of the model expression

The proposed expression for sludge production utilizes several input variables, as described in the previous three sections. Two of these input variables incorporate multiple regression equations that were developed in the previous chapter. Each of these equations utilizes sub-functions, which in turn describe the discrete input variables associated with these equations. Given the parameters defined in the three sections above, it is possible to write the basic model function as follows.

Equation 6.1

$$S_x = g_1 \cdot n_1 \cdot m_1 \cdot [P_x - R_x] + g_2 \cdot n_2 \cdot m_2 \cdot R_x + g_3 \cdot n_3 \cdot m_3 \cdot R_x$$

where
S_x = Sludge production at year x
P_x = Paper and paperboard production at year x
R_x = Paper and paperboard recycling at year x
$g_1 - g_3$ = Sludge generation rate in Mill Category I, II, and III
$m_1 - m_3$ = Modifying factor to determine organic woody/organic carbon composition of sludge[2]
$n_1 - n_3$ = Fraction of total sludge generation in Mill Category I, II, and III at the national level

This model can be used to calculate total sludge production by setting m_1, m_2, and m_3 equal to 1. Due to the inclusion of other models in the proposed expression, the sludge model necessarily provides outputs describing the same future scenarios as defined in Chapter 5.

[2] Taken from Table 6.1.

6.3 Model outcomes

6.3.1 Geographic distribution of sludge production

Trends are evident in the geographic distribution of future sludge production. In Figure 6.2, the distribution of sludge production in 1980 is shown. In this figure, the nations that are coloured a light green are those that are included in the model, while those coloured dark green were omitted on a statistical basis. The size of the pie chart on each nation indicates the relative contribution that that nation makes towards global sludge production.

It can be seen from the figure below that sludge production in 1980 was centered in North America and Europe, with Japan, China, and Brazil each contributing significant levels of sludge output. The incredibly large amount of sludge produced by the United States is a reflection of the dominance of the papermaking industry within this nation.

Note that this figure excludes the sludge produced by Germany, as in 1980 this nation was still politically separated into two sister-states.

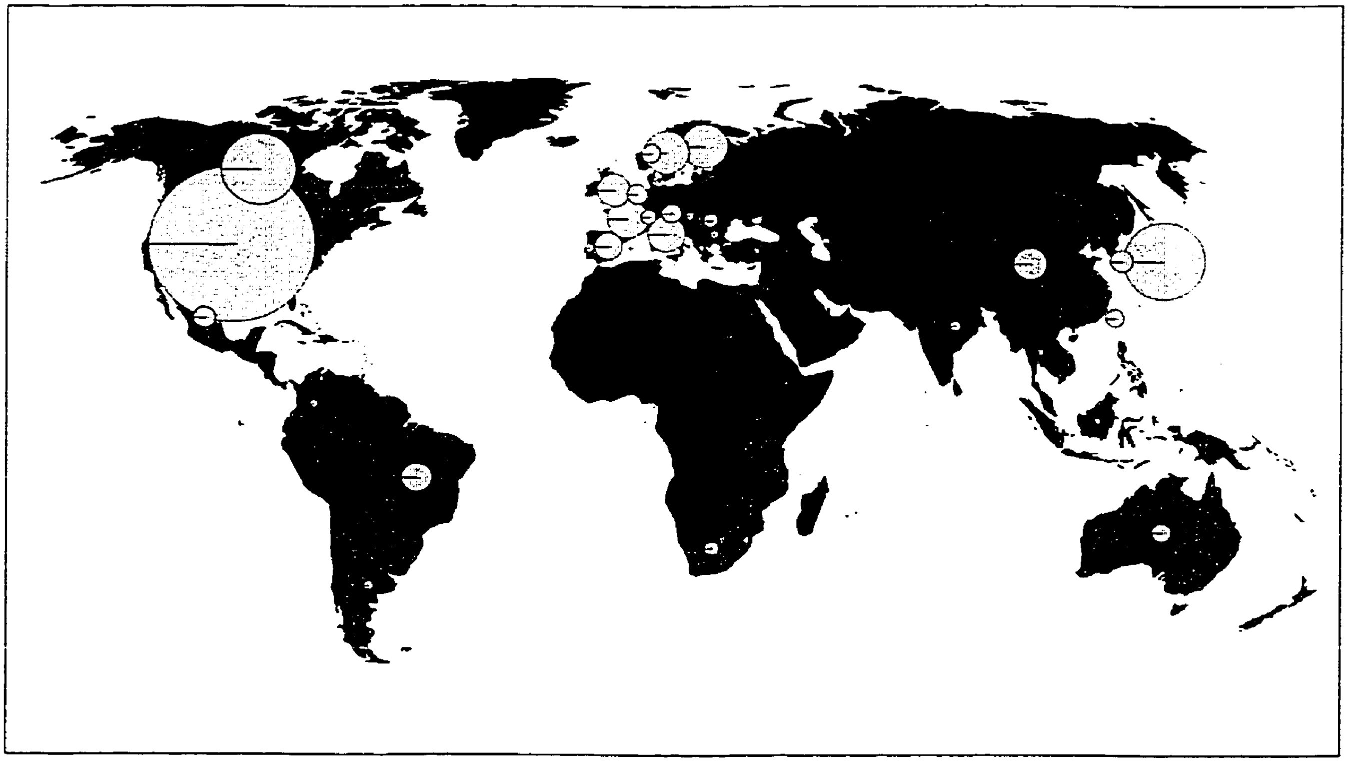


Figure 6.2 Estimated sludge production (1980) – Future Scenario 1

In Figure 6.3, the projected values of sludge production are shown for the year 2010. Here, the distribution of sludge production has begun to balance itself across three regions rather than two. A large amount of sludge is predicted to be produced in southeast Asia, as papermaking capacity comes online. This is met to some extent by increases in sludge production in North America and Europe, but the proportional increase is much greater in Asia.

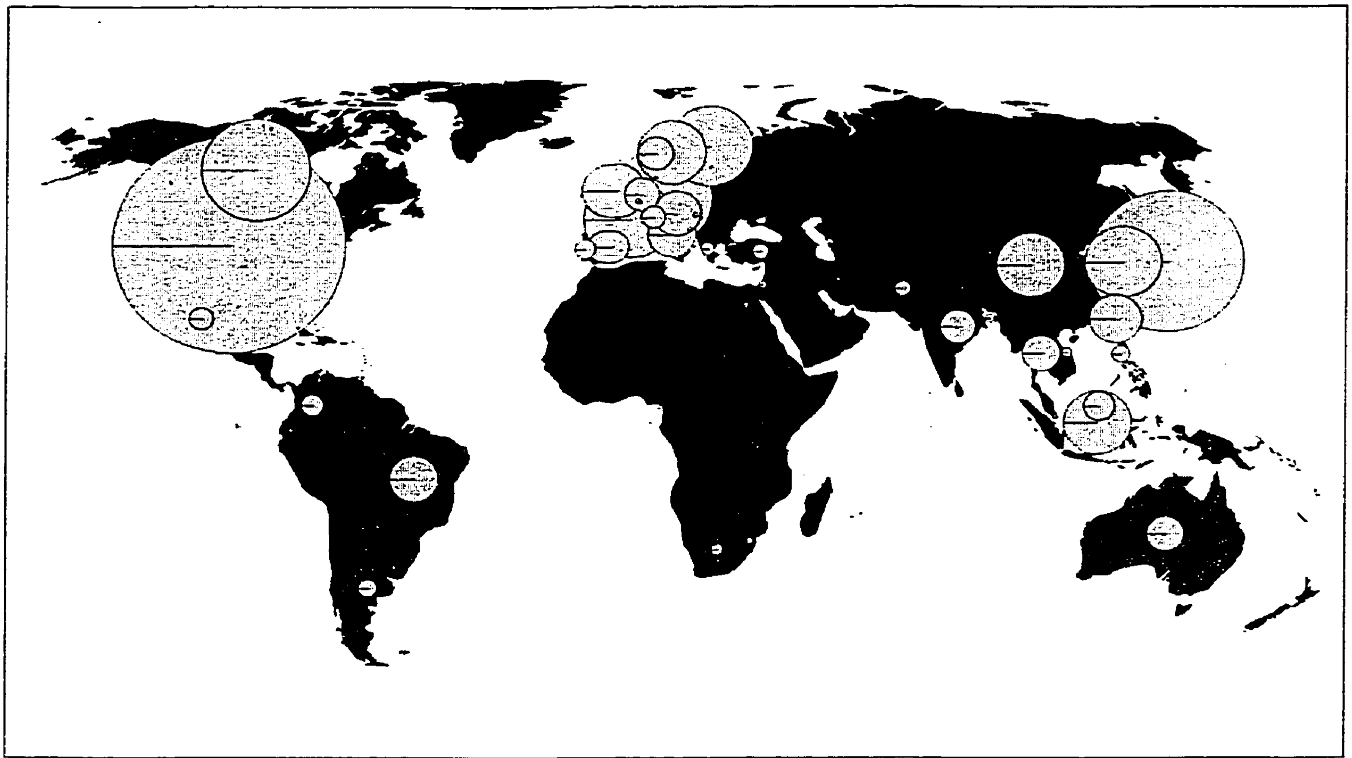


Figure 6.3 Projected sludge production (2010) – Future Scenario 1

Predicted sludge outputs in South America are quite low relative to the rest of the world, but represent a large proportional increase over 30 years. The projection for South America also reflects a trend that is currently dominating the South American industry, in which countries like Brazil are focusing on their role as suppliers of pulp rather than manufacturers of paper products. Development in the South American paper industry over the next decade could result in a much different future than these projections suggest.

Figure 6.4 illustrates the global distribution of papermill sludge production in the year 2050. By the end of the forecasting horizon, Asia has become the second-largest producer of papermill sludges behind North America. Development of the industry in Europe and North America has continued to increase sludge production, but at a much slower rate than in the Asian region.

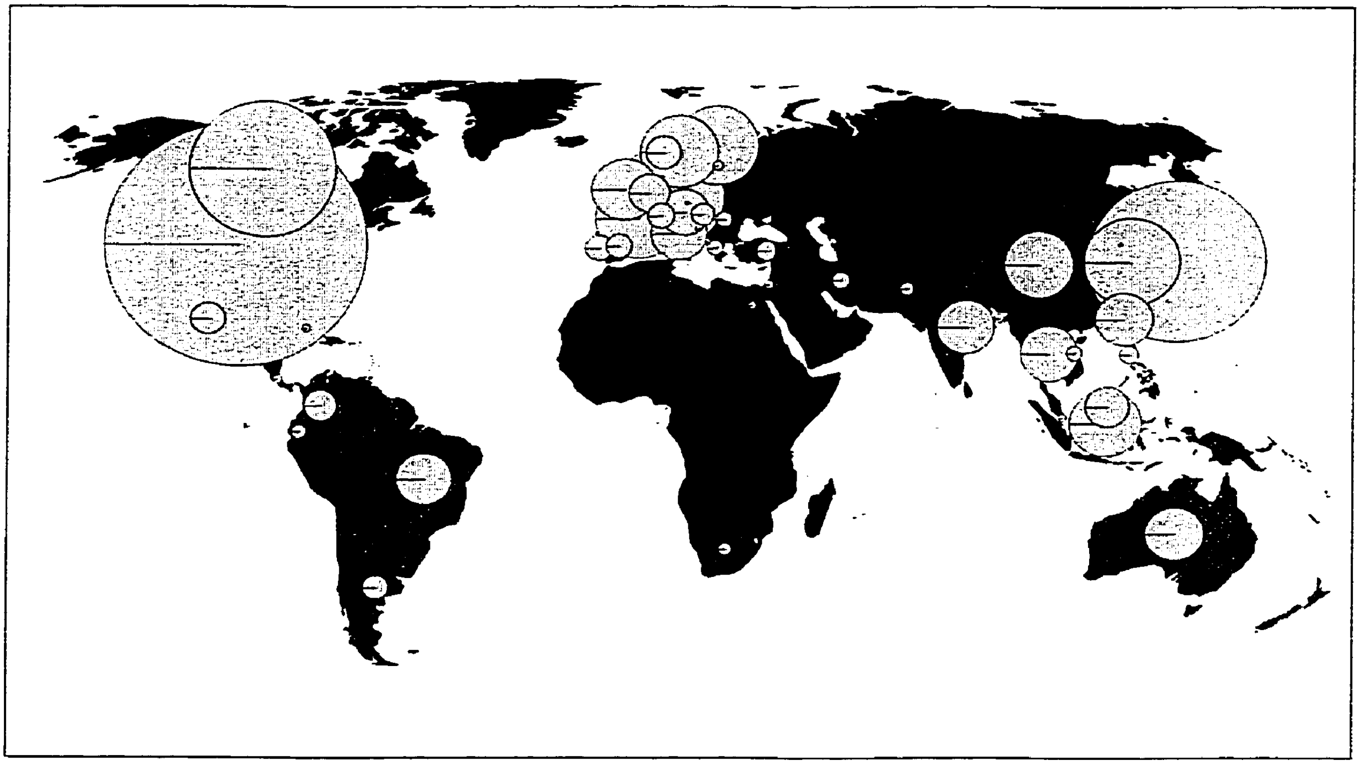


Figure 6.4 Projected sludge production (2050) – Future Scenario 1

Two major sources of potential error in the model are evident from this series of figures. One source of error stems from the fact that some regions exhibit future trends in sludge production that are based on current trends only. As the industry in these regions develop, these trends could change, and the future projections could be greatly influenced by these changes.

A second source of potential error is the number of countries for which no statistically valid model of paper production or recycling could be created. Most of Africa and all of the former Soviet nations were eliminated from the global model due the absence of good historical data, and the lack of clear trends in whatever data did exist. Whether or not these nations become major players in the global paper industry is uncertain. Certainly Russia, with one of the world's last frontier forests, has the potential to become a major contributor to the worldwide paper industry. The model is unable to anticipate the impact that these countries may have on sludge production in the future.

6.3.2 Sludge production by region

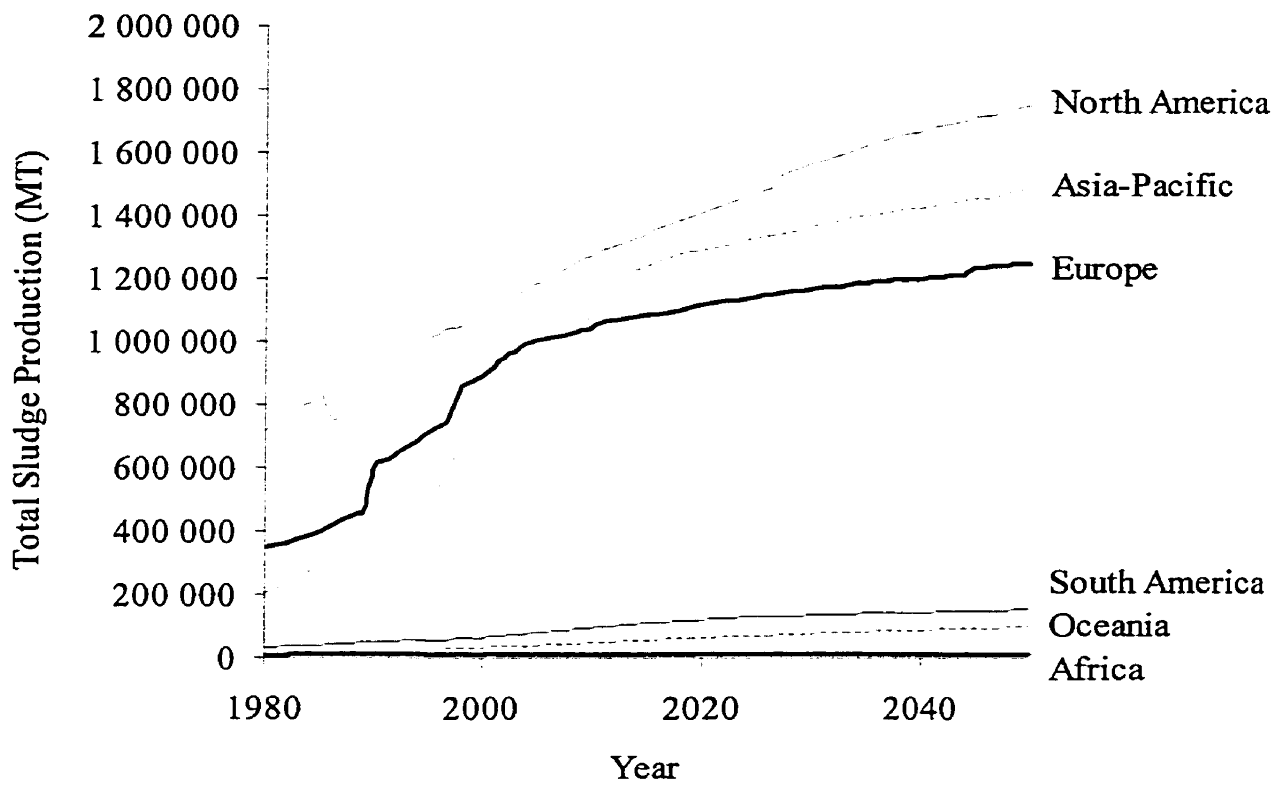


Figure 6.5 Future Scenario 1 - Projected sludge outputs by region, 1980-2050

In Figure 6.5, the historical trends in papermill sludge production are shown, as are the projected sludge outputs for the next 50 years. This future follows current trends in the manufacture of paper and paperboard products, and in the recycling of wastepaper.

It can be seen from this graph that North American production of sludge is higher than in any other region. It is anticipated to rise by almost 100% in the next 50 years, from 1 090 000 MT in 2000 to 1 750 000 MT in 2050. The Asia-Pacific region is anticipated to become the second-highest producer of sludge by the year 2010, and may produce about 1 480 000 MT of sludge by the year 2050. European trends in paper production and wastepaper recovery are slowly leveling out, and this is reflected in a fairly flat future projection that rises to only 1 250 000 MT of sludge by the year 2050. The three other regions of the world combined only forecasted to produce 265 000 MT of sludge by the year 2050.

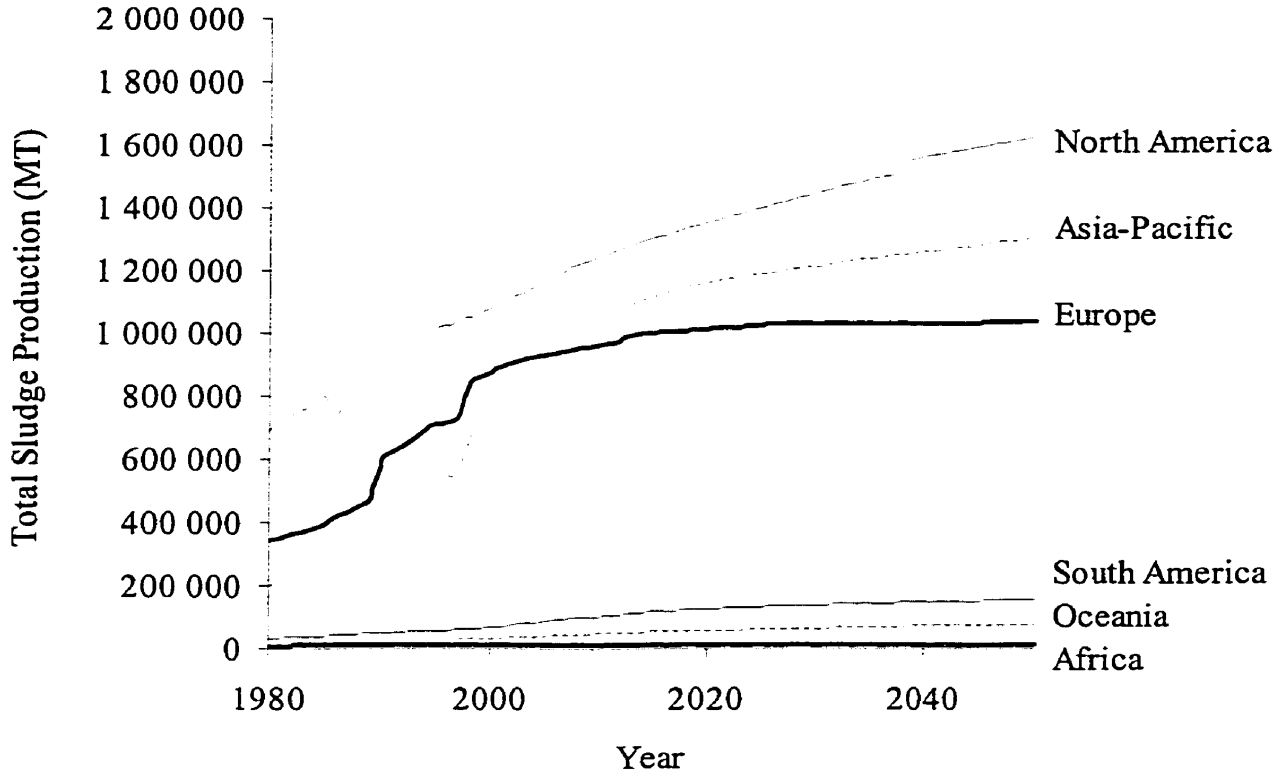


Figure 6.6 Future Scenario 2 - Projected sludge outputs by region, 1980-2050

Future scenario 2, as illustrated in Figure 6.6, represents a more industrial future. Perhaps not surprisingly, the amount of paper produced in this future is lower than in a future that simply follows current trends. This may be due to a decline in long-term fibre supply that offsets an initial short-term gain, and it may also be an indication of the lack of investment in recycling programs and alternative sources of fibre.

In this future, North American production of sludge in 2050 is forecast to be 1 625 000 MT/a, which is 130 000 MT/a less than by following current trends. The Asia-Pacific outlook passes the European forecast in 2008 rather than 2010, and ends at 1 306 000 MT/a or 174 000 MT less than in Future 1. The projections of European sludge output after 2025 are very flat, which indicates that in this scenario the European industry has reached maturity. The final projections for European sludge output are 1 040 000 MT/a, or 246 000 MT less than in Future 1.

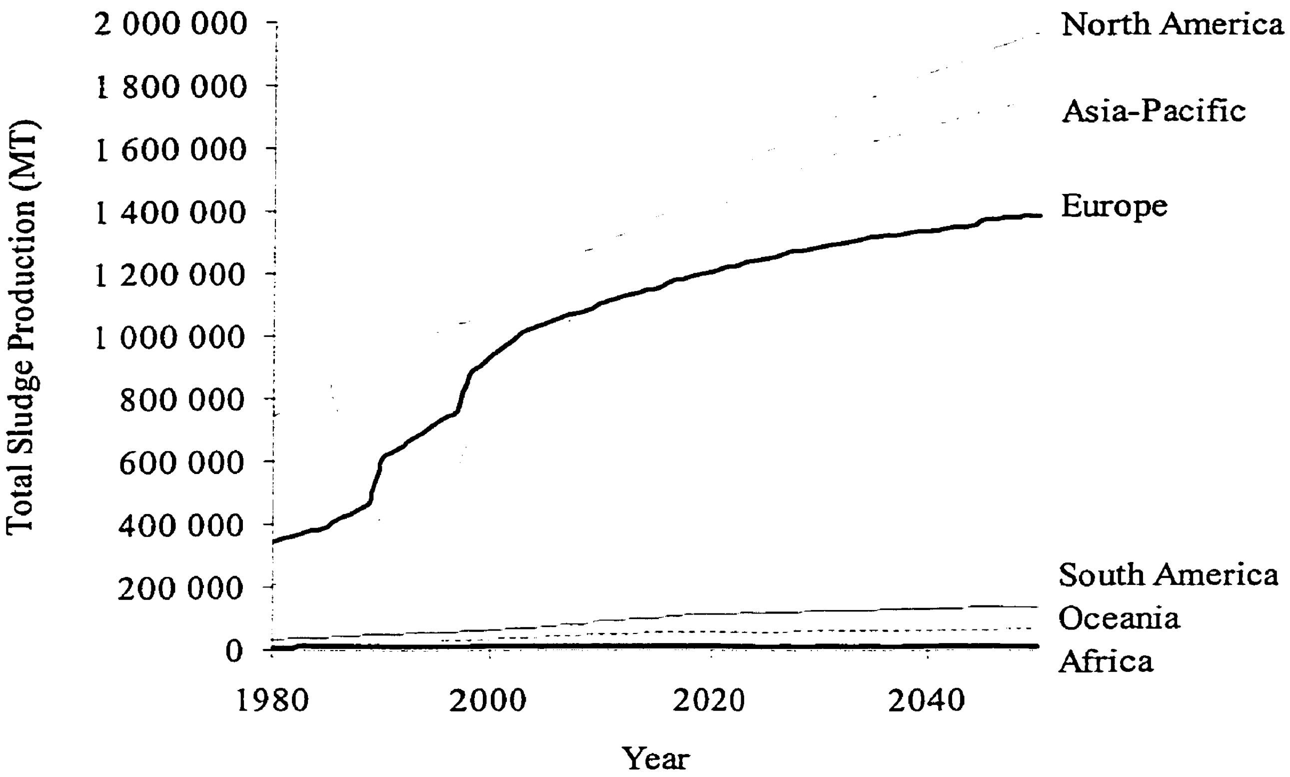


Figure 6.7 Future Scenario 3 - Projected sludge outputs by region, 1980-2050
Future scenario 3 represents a more environmental future, where short-term losses in fibre supply are offset by an increase in long-range supply. In this future, the population has been reduced slightly but is characterized by greater literacy and a lower urban component.

In this future, North America remains the largest producer of papermill sludge, producing 1 970 000 MT/a or 210 000 MT more sludge per year over current trends. In this future scenario, the Asian-Pacific industry very nearly surpasses the North American industry in 2022, but then loses ground over the last half of the forecast. It is anticipated that Asia may produce 1 763 000 MT/a of papermill sludge, which is 183 000 MT more than if current trends are followed. Finally, Europe again loses ground but remains in a growth phase, with sludge production anticipated to rise throughout the forecasting period. Ultimately, it is anticipated that European sludge outputs could rise to 1 390 000 MT/a, which represents additional sludge output of more than 140 000 MT.

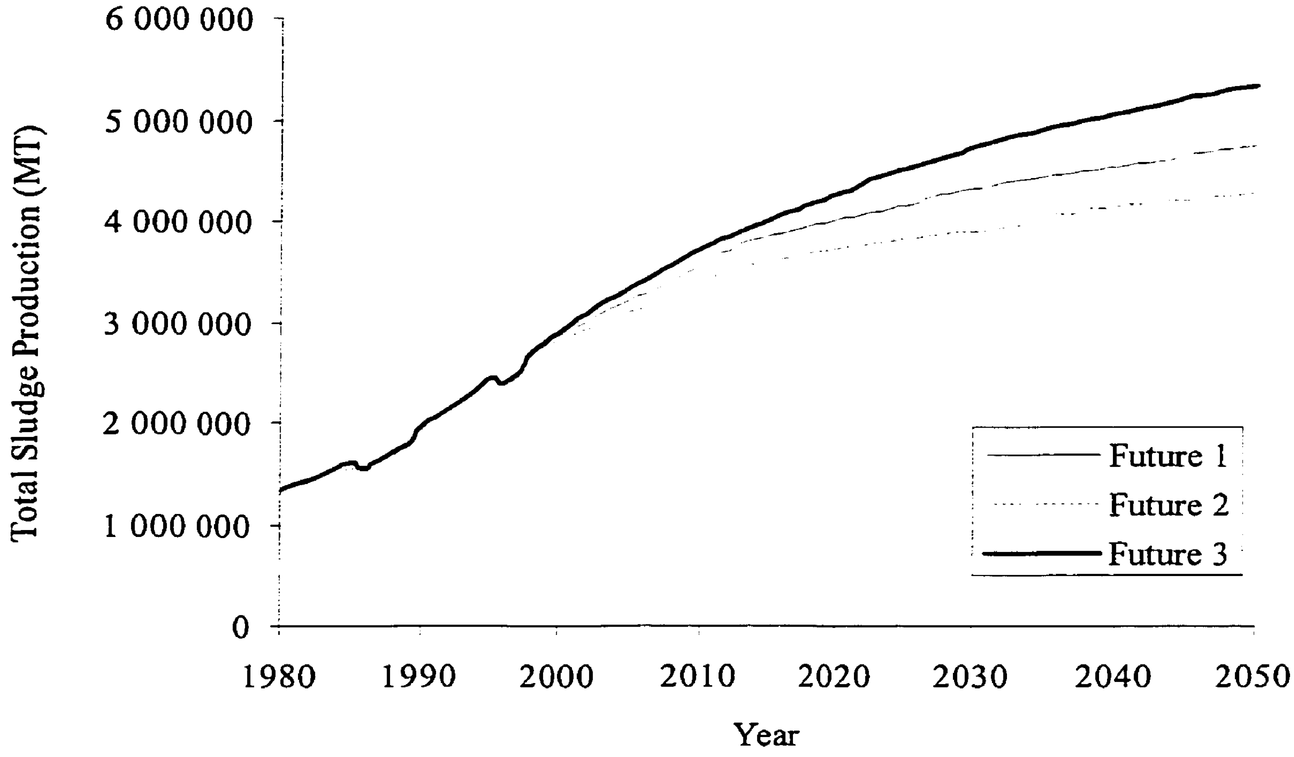


Figure 6.8 Projected global sludge production, 1980 – 2050

When the data shown in Figure 6.5, Figure 6.6, and Figure 6.7 are tabulated, the global total sludge production can be derived. Figure 6.8 shows the predicted range of global sludge production across the three defined scenarios. It is anticipated that global sludge production could rise from 2 900 000 MT/a in the year 2000 to between 4 300 000 MT/a and 5 400 000 MT/a in the year 2050. This represents anywhere from a 48% to 86% rise in global sludge production over the 50 year forecasting period.

6.3.3 Implications of sludge production

The figures in the previous section have demonstrated that sludge production will definitely rise in the future. The degree to which sludge production rises depends greatly upon the actions that are taken in the future. The models indicate that seemingly environmental choices, such as increasing recycling programs, decreasing deforestation and increasing the establishment of plantations, can result in higher production of papermill sludges, creating a disposal problem and contributing to pollution.

There is an implication for policymakers if sludge production should rise to this extent. Establishing guidelines for the disposal of sludge now can direct future waste towards one of the three options currently available for sludge disposal. Incineration, landfill, and recycling of the material could feasibly be joined by other options if economic and legal incentives are provided to the industry.

In terms of scale, it is obvious that the three regions that produce the majority of sludge, North America, Europe, and Asia, will have the greatest problem to deal with in terms of pure economics. Much more physical landfill space will be required for disposal in the future. As landfill sites become scarcer and tipping fees increase, the use of alternative disposal techniques, including incineration, will be embraced more readily. The economic and environmental costs of alternative disposal practices should be addressed now.

In terms of proportional increases in sludge production, a much different picture emerges, as shown in Figure 6.9.

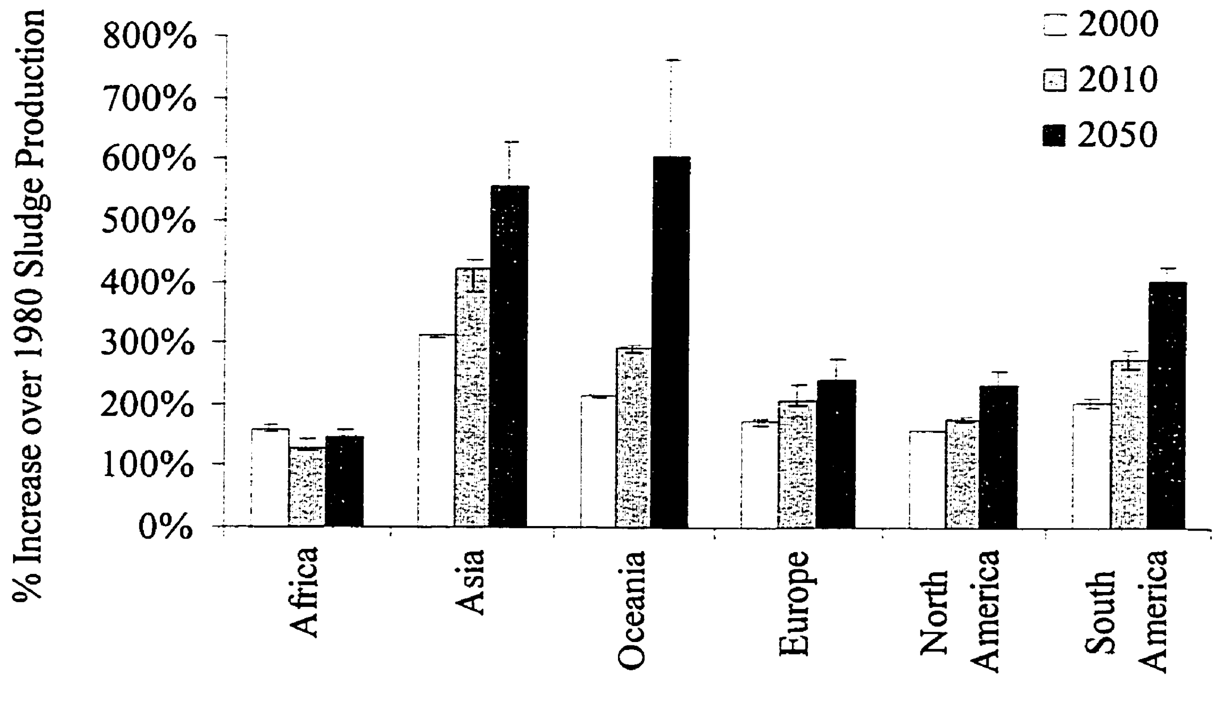


Figure 6.9 Projected proportional increases in sludge production by region, 2000-2050. Error bars indicate limits set by 3 future scenarios

In this graph, it can be seen that three regions have a much lower proportional increase in sludge disposal to deal with. Africa, North America, and Europe will all experience a low proportional rise in sludge production, which means that these regions may be better equipped to deal with the problem than the other three regions.

In Asia, Oceania, and South America, however, the proportional increase in sludge production is anticipated to be much higher. In Asia, the amount of sludge produced could increase by almost 600% over 1980 levels, and in Oceania, this figure could be as high as 800%. Essentially, this means that for ton of sludge produced in 1980, eight tons could be produced by 2050. This could have strong ramifications in terms of landfill space or incinerator capacity required. While the company normally picks up the economic cost of disposal, the environmental costs of increased sludge production could have strong ramifications for national governments.

According to North American figures, about 45% of papermill sludge is currently landfilled, while an additional 45-50% is incinerated for power or disposal and 5% is used as a land application for soil enrichment (Badar and Cutbirth 1993, Pickell and Wunderlich 1995, NCASI 1991). Using these figures, it was possible to create three arbitrary scenarios for global papermill sludge disposal, as shown in Figure 6.10.

In the first scenario for sludge disposal (A), the amount of sludge to be incinerated and landfilled is doubled, resulting in twice as much load on landfills and incinerators by the year 2050. By decreasing the amount of landfill or incineration that is permitted, an additional 1 000 000 MT of sludge is diverted to the alternative option (B and C).

These scenarios are limited in that they assume that one disposal technique can always be substituted for the other. There is a very real possibility that increasing worries over climate change and lack of space for new landfill sites will add to the costs of each of these forms of disposal. Should this occur, the only real alternative today is in land application. Unfortunately, land application of sludge has been shown to be a very costly disposal technique. One last option, which involves recycling the sludge material, has been explored to some extent in the literature but does not yet provide a feasible option for handling millions of tons of dry sludge material.

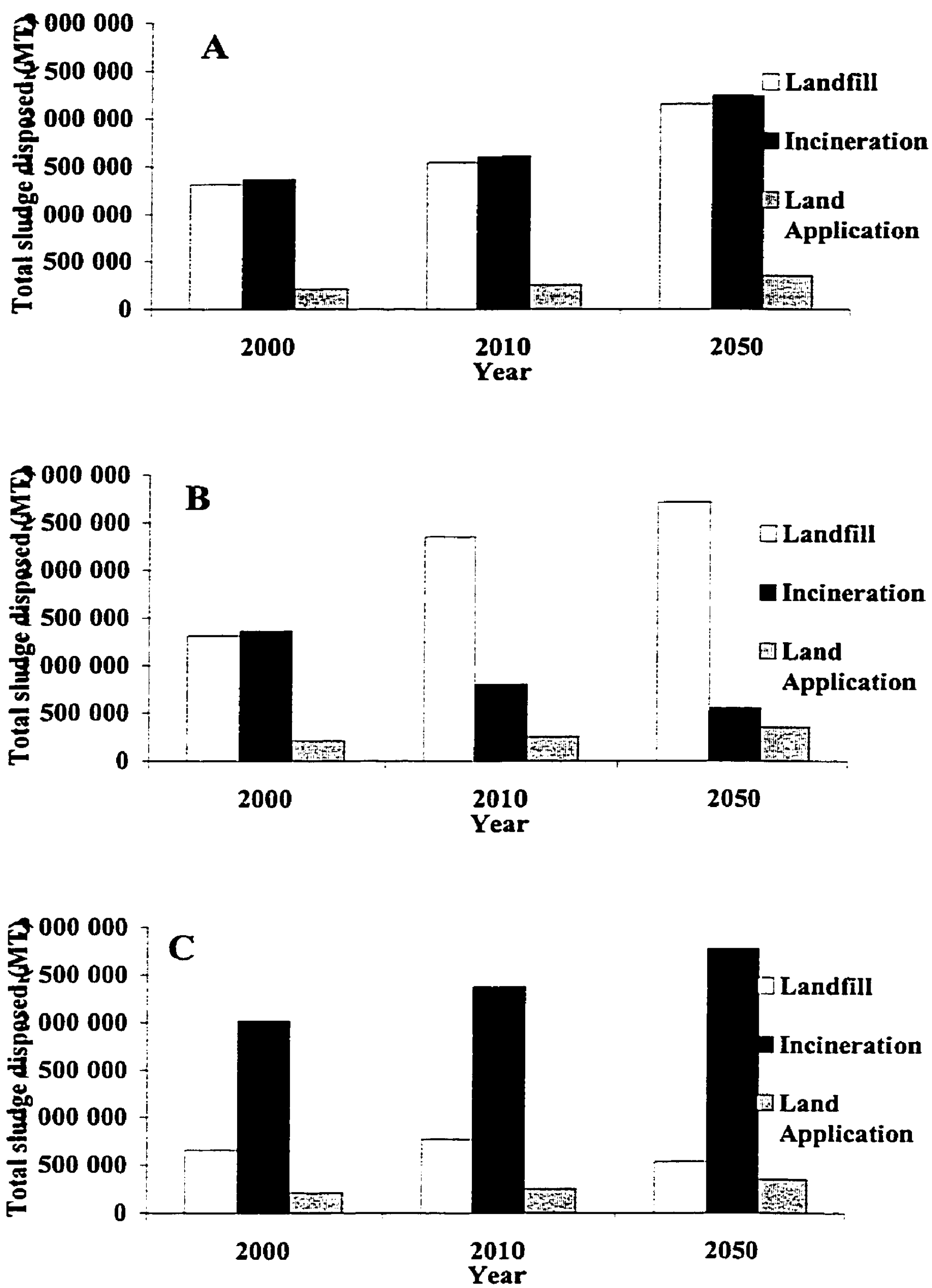


Figure 6.10 Implications of sludge disposal techniques

A. Disposal follows current trends

B. Incineration reduced by 75% by 2050

C. Landfill reduced by 75% by 2050

6.4 Options for sludge disposal

6.4.1 Reduction of sludge through fibre recovery

One option for disposal of sludge is to recover fibre from within the sludge matrix. Many attempts have been made at this, as discussed in Section 2.3 of the literature review. One problem with fibre recovery from sludge is that removing fibre often destabilizes the matrix of the sludge material that is left, making it harder to deal with in traditional disposal practices. In addition, there are high costs to fibre recovery that offset any gains in material that may be experienced.

Using the global sludge production model, it is possible to estimate the total amount of woody organic material that is present in global sludge, as shown in Figure 6.11.

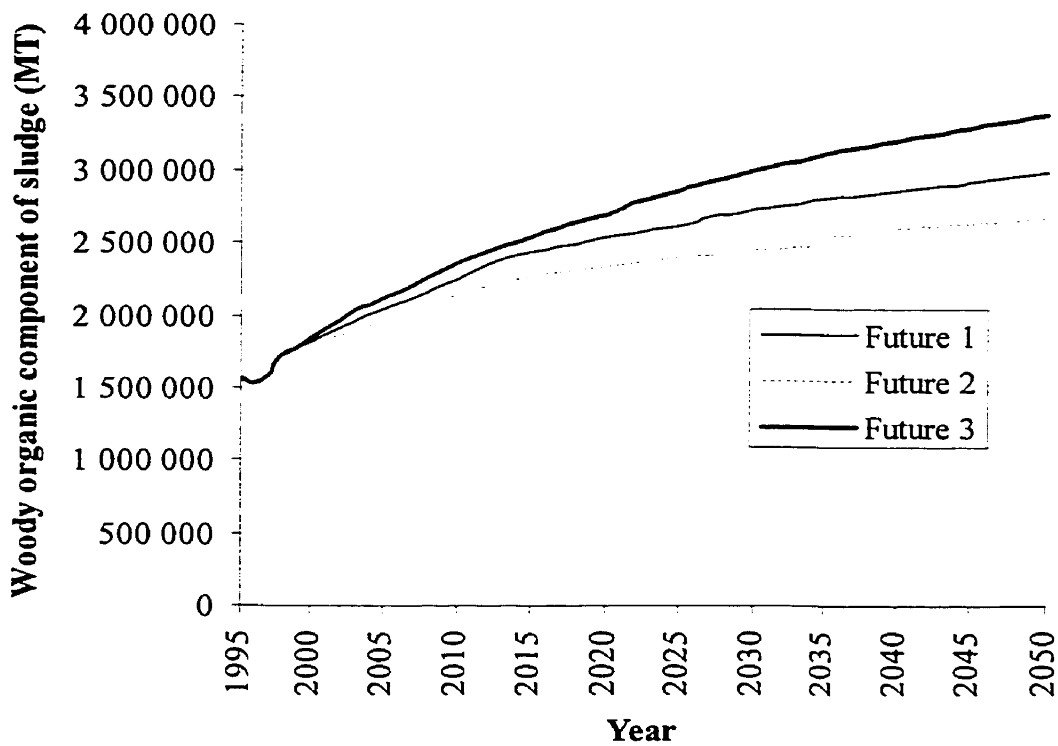


Figure 6.11 Global production of woody organic material as a component of sludge (1995-2050)

The graph above illustrates the estimated trends for woody organic loss through papermill sludge disposal. The actual amount is quite high, with data at the baseline hovering around 1.5 million

MT/a of material. It has been shown in Chapter 3 that a great deal of this material actually consists of fines, but a significant component is comprised of fibre that might be reused in a paper or board product.

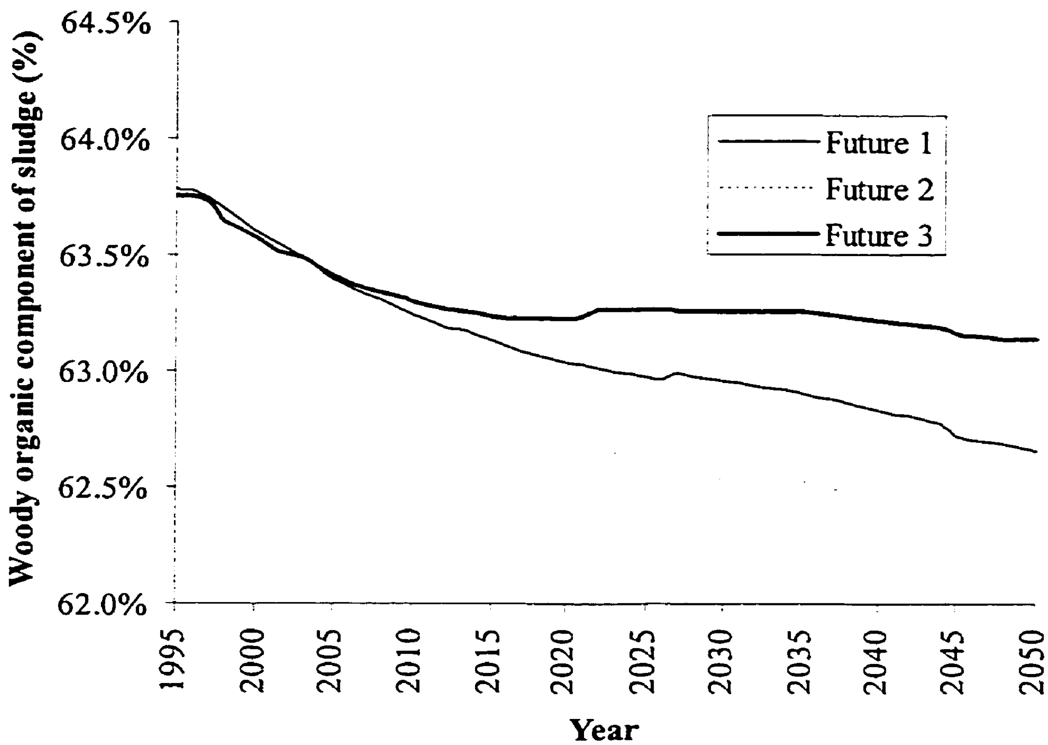


Figure 6.12 Proportion of woody organic material in sludge (%)

Due to the advent of recycling, the amount of woody organic material present in the sludge is actually expected to decline slightly over the next 50 years. The sludge gleaned from recycling operations does not contain as much fibre, and increasing recycling during the forecasting period means that less woody organic material is ending up within the sludge itself.

While the woody component makes up a large fraction of sludge solids, it is not recommended that recovery of this component *in situ* be pursued as a viable option in reducing sludge disposal costs. Should the decision be made to reduce costs by reducing the woody component within the sludge, the ideal approach would be to recover every possible fibre during the primary screening and cleaning processes. Moreover, the fact that the woody component of sludge is declining, however slightly, means that the amount of raw material to be recycled from the sludge will be lower in the future. This does not bode well for the development of new recovery practices.

6.4.2 Sludge disposal as part of the forest products carbon cycle

Using the global sludge production model, it is possible to estimate the total amount of woody carbon, or carbon that originates in wood fibres, that is present in global sludge. This is shown in Figure 6.13.

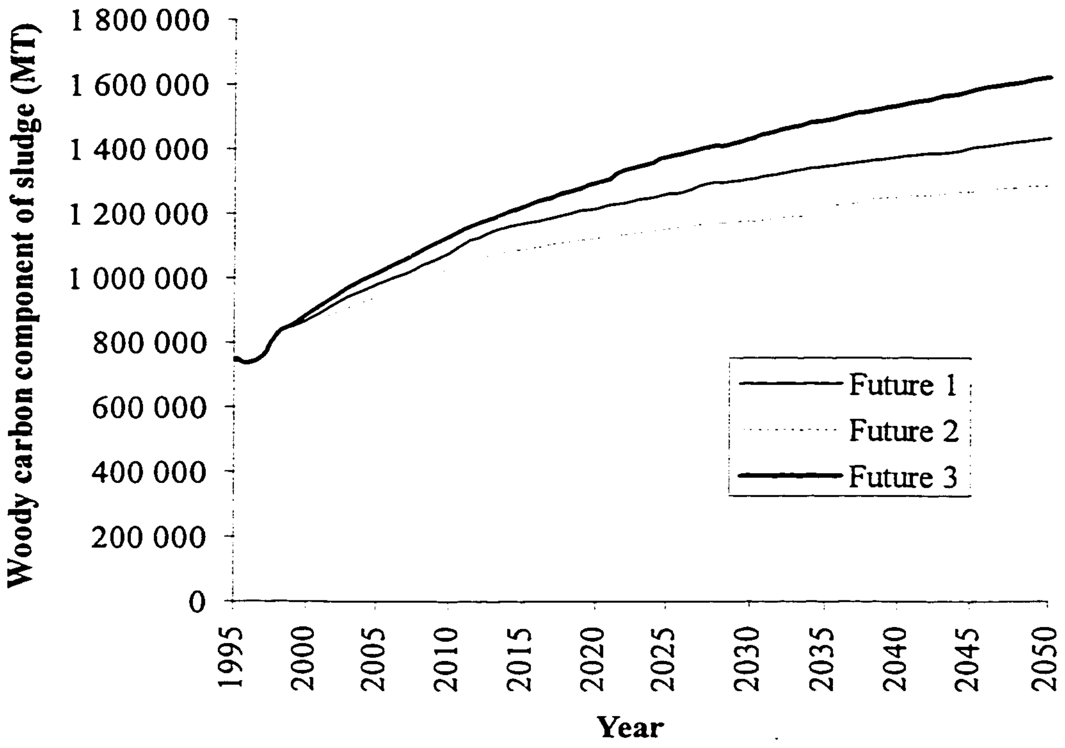


Figure 6.13 Woody carbon produced as a component of papermill sludge (MT)

The amount of 'woody' carbon that is incorporated in papermill sludges is estimated to double in the 50 year forecasting period, from about 800 000 MT/a to between 1 200 000 and 1 600 000 MT/a in 2050. The first observation is that this is an extremely small portion of the overall global carbon cycle, but potentially a significant portion of the forest products carbon cycle. Estimates of the sequestering ability of the forest products carbon cycle range around 20 million MT/a (Houghton et al. 1999, Kellomäki and Karjalainen 1996, Nabuurs 1996). This does not include fast-decomposing materials, which includes paper.

If the estimates provided in this model are correct, there are two important implications for the forest products industry. One is that 800 000 MT/a of carbon, representing approximately 4% of the carbon sequestered annually by the forest products industry, is available for manipulation by the industry. This could have serious repercussions if carbon credits become a serious proposition in the ongoing discussion about climate change, although the likelihood of this eventuality remains to be seen.

The second important implication is that a significant portion of the carbon associated with the pulp and paper industry, which until now is normally considered to be locked into short-term products and therefore not useful for sequestering carbon, is actually being carried by the waste stream. If this material is landfilled, the carbon that is associated with the sludge is essentially being sequestered.

Given these observations, it is important to know if there is a trend in the amount of woody carbon contained in sludge. The proportional amount of carbon present in mixed papermill sludge is represented in Figure 6.14. While there is a very slight downward trend in the amount of carbon held within the sludge, the actual decline is minimal. It can be concluded that carbon levels remain at approximately the same level, despite the changes in recycled paper production.

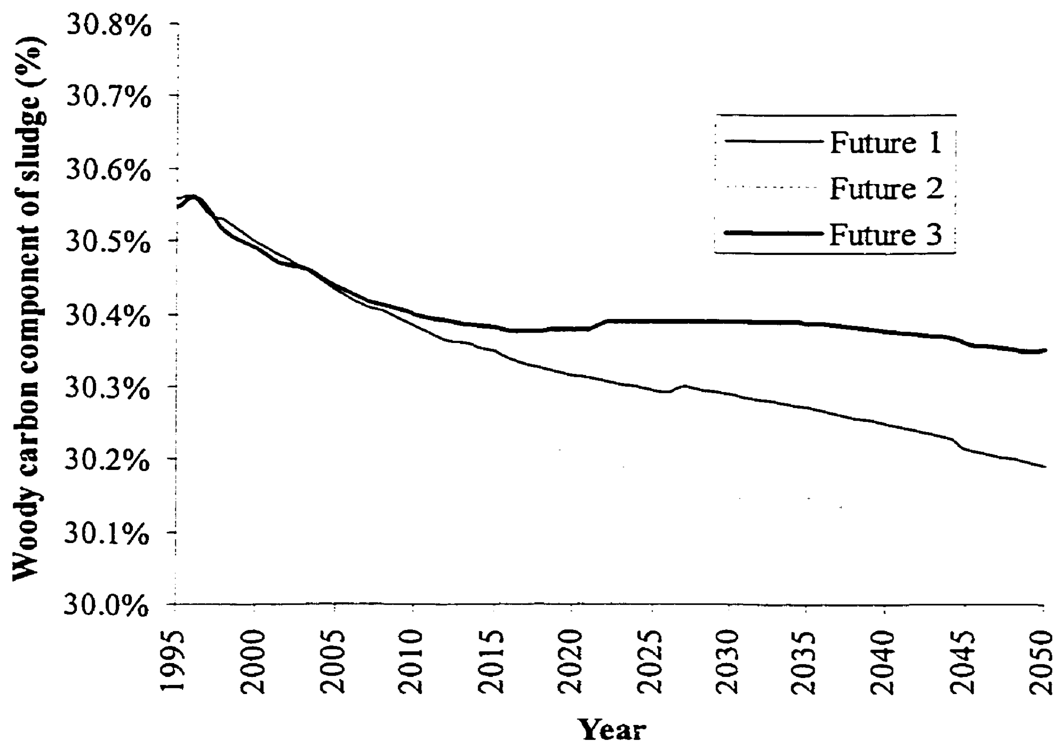


Figure 6.14 Proportion of carbon from woody organic material in sludge (%)

6.4.3 Implications of sludge disposal practices

Sludge disposal practices may come into question as the amount of sludge being produced continues to rise. Furthermore, with the rapid consolidation of the paper industry, the importance of large multinational companies creating and maintaining strategies to deal with papermill sludge disposal becomes even more crucial. Currently, recycling fibre is not a widely pursued option due to high initial costs and low market value for fibre. The research does not support further inquiries in this direction at this time, although changing economic conditions could improve the feasibility of this option. Land application of sludges is also an option, but has been found to be expensive and produces varying results. The most commonly used practices for sludge disposal today are incineration and landfilling, and these practices will not change overnight. Given the evidence that sludge may comprise a significant portion of the forest products carbon cycle, it is necessary to re-evaluate these practices.

Incineration

A large portion of sludge being produced by papermills is being disposed of through incineration for power. In these cases, the role of the decision maker is to balance the savings gained from generating power on site, and the costs of complying with increasingly strict environmental regulations. In fact, it is shown in the literature that papermill sludge has a low heating value, and the emissions of greenhouse gases associated with burning this material may offset any energy gained.

From an environmental perspective, a question that needs to be examined in every installation is whether or not the burning of sludge offsets the use of fossil fuels enough to justify its use. The answer to this question normally lies with the accountability of the power company that is providing service. Often power is purchased through a grid, and determining its exact origin (hydro-electric, nuclear, or fossil-fuel) can be difficult.

From an economic perspective, a question that needs to be examined is whether or not carbon credits are going to be enacted, and how these credits will be counted. Incinerating sludge for power may offset the burning of more dangerous fossil fuels, which should deserve a carbon credit of some form.

Landfilling

The other widely used disposal technique for papermill sludges is landfilling. This method of disposal is becoming more difficult in North America and Europe as environmental regulations grow more stringent (Raitio 1992, Harrison 1989). Tipping fees are rising, and the practice of creating company-owned landfills near mills may not be feasible in all jurisdictions. Properly designed landfills are expensive and require constant maintenance.

From an environmental perspective, the question that needs to be asked is whether or not the landfilling of sludge material can be considered a sequestering action. Determining the usefulness of landfills to sequester carbon is highly dependent on the quality of the landfill construction, which of course incurs extra costs.

From an economic perspective, the question that needs to be answered is in reference to carbon credits. If carbon credits are assigned to the mills for landfilling sludge and sequestering the organic carbon associated with this material, will the credits be enough to offset the cost of actually landfilling this material.

6.5 Conclusions

The principal conclusions derived from this section of study are as follows.

1. Projections of the geographic distribution of sludge production indicate that three global regions dominate most sludge production. North America and Europe are regions in which the papermaking industry has matured, while Asia-Pacific is a region experiencing tremendous growth.

2. North America will remain the dominant producer of sludge well into the twenty-first century. At current rates of growth, the countries of southeast Asia will replace Europe as the second highest sludge producing region early in the forecast period.

3. By the year 2050, global sludge production is projected to rise between 46% and 86% over 2000 levels. This rise means that current sludge production levels of 2 900 000 MT/a will increase to somewhere between 4 300 000 MT/a and 5 400 000 MT/a by 2050, creating up to 2 500 000 MT/a of extra sludge to be disposed of.

4. In the year 2000, about 2 000 000 MT of woody organic material was incorporated into sludge. This may increase by another 1 500 000 MT/a by the year 2050. This amount of

wood fibre, while significant, does not justify the expenditure of developing technology to recover this fibre. Furthermore, the proportion of woody organic material found in papermill sludge is found to decline slightly over the 50-year forecasting period.

5. In the year 2000, 800 000 MT of woody carbon was incorporated into sludge. This represents approximately 4% of the carbon sequestered annually by the forest products industry, which in turn indicates that a significant portion of the carbon associated with the pulp and paper industry is actually being carried by the waste stream and has the potential to be sequestered.

6. Based on the observations in the previous section, the most beneficial way of dealing with the problem of increasing levels of papermill sludge production might be consider it as part of the carbon cycle in order to gain potential carbon credits for its disposal, through whatever means is most economical and environmentally friendly.

7 Conclusions

The principal conclusions of the study are as follows.

1. Based on a study of five Ontario and one Quebec paper mills, it can be concluded that it is possible to quantify the woody organic component of papermill sludge. The quantifying technique as presented provides a new and innovative approach towards identifying wood components within a matrix of foreign material, and this has great potential as a tool in conducting life-cycle analyses on a wide array of wood products. Several fundamental facts that describe sludge have been uncovered:

    a. The chemistry of mixed papermill sludge is dominated by woody organic material, which compose more than 60% of the total sludge solids on average.

    b. The chemical characteristics of sludge show a relationship to the presence or absence of recovered fibres in the furnish.

    c. Alphacellulose is the single most common woody organic component found in papermill sludge. It is found in proportionally smaller amounts in the sludges of recovered paper mills.

    d. Lignin is the second most common woody organic component found in papermill sludge. It is found in higher proportions in the sludges of recovered paper mills.

From the data presented, it may be concluded that the presence of free cellulose, in the form of fines, broken fibres, or loose fibrils, is more closely related to the use of virgin fibre than with recovered fibre. The presence of additional cellulose in the sludge of a virgin paper mill may indicate that improvements can be made in these processes, in order to recover these fibres and fines before they enter the waste stream.

2. Based on the analysis of the chemical components of papermill sludge over time and from six different papermills, it can be shown that the chemical characteristics of sludge are related to certain types of papermills. Virgin mills (Category I), mills producing recovered paper without deinking (Category II), and mills producing recovered paper with deinking (Category III) were separated by significant differences in the organic chemical components of the woody fraction. This analysis further described the fundamental chemistry of papermill sludge:

    a. Alphacellulose is the most variable woody component found within sludges in terms of temporal based shifts. Long-term observations confirm that changes in process or furnish can greatly influence the alphacellulose component of sludge, which further supports the hypothesis that free alphacellulose, in the form of broken fibrils or fines, is more closely associated with virgin fibre sources.

    b. Observed levels of holocellulose, Klason lignin, and soluble lignin, as measured in sludge from multiple mills within the three assigned mill categories, follow a normal or t-distribution, indicating that the hypothesized mill categories resemble a normal population.

    c. The physical characteristics of papermill sludge fibres, in terms of length and percent fines, do not change significantly from mill to mill. The coarseness of fibres within papermill sludge is variable, and reflects differences in furnish and in processing.

    d. The woody organic component of sludge is significantly different in the three mill categories described, comprising 67% of Category I sludge, 64% of Category II sludge, and 55% of Category III sludge.

3. The proposed models for paper production and wastepaper recycling were very successful, accounting for 94 and 96% of global totals in the baseline year. The proposed model for paper consumption was less successful, with only 81% of global consumption accounted for in the baseline year.

    a. The combination of social and physical factors in the modeling exercise was supported by the geographic distribution of countries where each factor was statistically significant. Literacy rates and population density were most prominently recognized as correlating factors in Africa, Asia and South America, where the number of developing nations currently undergoing rapid social change is very high. Fibre supply from forests, plantations, and nonwoods could be related to countries where these sources of supply are in abundance.

    b. The model for paperboard production was statistically sound in 55 countries and explained 94% of total world paper production in the baseline year (1995). Potential problems for future forecasting are related to the countries that were not incorporated into the model. Due to poor correlations or bad data, the model eliminated countries that are currently or may become dominant forces in the supply of pulp or paper products, such as New Zealand and Russia.

    c. The model for wastepaper recycling was found to be statistically sound in 38 countries, and explained 96% of the total world wastepaper recycling in the baseline year (1995). The principal concern for future error in the projection of wastepaper recycling is tied to the fact that only countries seriously involved in wastepaper recycling during the baseline year are considered within the model. Countries that as of 1995 had not begun to recycle wastepaper to a significant extent could not successfully match the criteria set out in the model. Thus, any additional countries that enter the recycling market before the model horizon are not included in the forecast.

    d. The model for paper consumption could only explain 81% of the global consumption of paper. The drawback to this model error was linked to the fact that consumption of all forest products is linked to imports and to economic factors that were not included in the model.

4. Projections of the geographic distribution of sludge production indicate that three global regions dominate most sludge production. North America and Europe are regions in which the papermaking industry has matured, while Asia-Pacific is a region experiencing tremendous growth. The most important conclusions that can be made by analysis of this model are that:

    a. North America will remain the dominant producer of sludge well into the twenty-first century. At current rates of growth, the countries of southeast Asia will replace Europe as the second highest sludge producing region early in the forecast period.

    b. By the year 2050, global sludge production is projected to rise between 46% and 86% over 2000 levels. This rise means that up to 2 500 000 MT/a of extra sludge will be produced, and will have to be discarded or recycled.

    c. In the year 2000, about 2 000 000 MT/a of woody organic material is incorporated into sludge. This may increase by another 1 500 000 MT/a. This amount of wood fibre, while significant, does not justify the expenditure of developing technology to recover this fibre. Furthermore, the proportion of woody organic material found in papermill sludge is found to decline slightly over the 50-year forecasting period.

5. The role of sludge in the forest products carbon cycle has been identified as being larger than previously suspected. Although the forest products carbon cycle is not fully understood, estimates place the total carbon sequestered in forest products at about 20 000 000 MT/a (1995). The estimate for the organic carbon content of sludge is about 800 000 MT/a. This amounts to about 4% of the total estimated forest products carbon cycle. What is important about this estimate is that sludge is a waste product, which is completely controlled by the industry. A very large component of the overall forest products carbon cycle can be utilized directly by the industry.

    a. In the year 2000, 800 000 MT/a of woody carbon was incorporated into sludge. This represents approximately 4% of the carbon sequestered annually by the forest products industry, which in turn indicates that a significant portion of the carbon associated with the pulp and paper industry is actually being carried by the waste stream and has the potential to be sequestered.

    b. If carbon credits are introduced, the disposal techniques that are currently being used, principally landfilling and incineration, would still be viable options for the disposal of sludge. The incineration of sludge might provide carbon credits to the industry, as this course of action provides an offset from the burning of fossil fuels. The landfilling of sludge should also provide a carbon credit, as this option results in the sequestering of a significant portion of the carbon cycle.

As a general conclusion, it can be stated that the role of papermill sludge in the forest products industry carbon cycle has been greatly underestimated. In the author's option, the most beneficial way of dealing with the problem of increasing levels of papermill sludge production might be to consider the possibility of harnessing this portion of the carbon cycle. Such an approach could result in both economic and environmental benefits, for the industry and for the world at large.

8 Recommendations for Future Work

Two projects have been targeted as necessary steps to build upon this study.

8.1 An analysis of the forest products carbon cycle

This project has elucidated one small portion of the forest products carbon cycle. In fact, there are very large holes in the literature regarding the role of forest products in earth's comprehensive carbon cycle. It is recognized that products can sequester a portion of carbon, but estimates of how long this sequestration will last, and how much carbon is actually present in these products, are only rough guesses made by modelers eager to approach the global problem. The author suggests an approach similar to that taken in this study, where an in-depth review can be carried out on a few representative installations to provide fundamental data, which in turn can be applied on a regional or global scale as the researcher wishes.

Ideally, this recommended study would incorporate several facets of forestry and wood science within a single research framework. Many researchers could eventually be part of this framework, all of whom could be contributing to a single synthesis model.

The most important stages of this research project would involve the following:

- Identification of the carbon conversion rate associated with harvesting, processing, and use of different species for different forest products; an effective rate of conversion between the carbon in a tree and the carbon in various products must be devised.
- Full life-cycle analysis of different forest products, including solid and engineered wood and paper products, in order to identify the ultimate disposition of woody carbon components.
- Identification and measurement of the carbon co-generation associated with forestry, wood conversion, recycling, and forest products use.

8.2 Development of an econometric model for paper production and wastepaper recycling

One of the guiding principles embraced in the Global Fibre Supply Model, of which the author was a key part, was importance of having multiple predictive models to verify that future predictions were not completely unrealistic. It was suggested that for every non-econometric model developed, such as the one presented in this study, an econometric model should be developed for the purposes of cross-checking the datasets produced.

With this in mind, the author suggests that a second model be built in order to examine the same output variables as identified in this project. Instead of using social and physical indicators, as was done here, the input variables could be based upon the economic factors identified but not used in this study.

At the conclusion of this model development, it should be possible to create a synthesis model that incorporates the best of both. Such a model might be more successful in forecasting future paper production, recovery, and even supply in countries where the study was unable to make any predictions.

8.3 Development of improved methods for sludge reduction through fibre recovery

In order to reduce future needs for sludge disposal, a more serious look should be taken at fibre recovery from the sludge stream. The work would revolve around improving fibre recovery within the mill through the addition of cleaners and scrubbers to the primary effluent treatment system.

The primary objective of this work should be to determine the lower limits for fibre content in sludge, in order to retain the desirable effects that fibre has on sludge properties (i.e. dewaterability, stability for use in landfill operations) while optimizing the overall fibre recovery for the mill. Sludges of various fibre content should be examined for each of these parameters. The possibility of introducing a different fibrous substance to improve sludge stability and dewaterability after fibre removal should be examined.

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Appendix 1:
Paper and paperboard consumption – significant input variables

Numbers in the chart below indicate the partial r^2 values returned by SAS through stepwise regression, indicating the significant input variables and the relative importance of each variable to the overall correlation coefficient. Highlighted rows indicate countries where the data run was accepted.

Country	Indiscrete	Population	Nonwoods	Plantation	Density	Literacy	Forests	Total r^2
Afghanistan					0.30			**0.30**
Albania					0.04	0.02	0.89	**0.95**
Andorra		0.49				0.31		**0.80**
Anguilla		0.16			0.15			**0.31**
Antigua & Barbuda		0.60				0.12		**0.73**
Argentina				0.72				**0.72**
Aruba					0.56			**0.56**
Australia							0.88	**0.88**
Austria					0.03		0.89	**0.92**
Bahamas		0.96						**0.96**
Bahrain	0.14					0.18		**0.31**
Bangladesh				0.96				**0.96**
Barbados					0.16			**0.16**
Belgium						0.91		**0.91**
Belgium-Luxembourg						0.91		**0.91**
Bermuda					0.54			**0.54**
Bhutan				0.75				**0.75**
Bolivia		0.17				0.13	0.46	**0.75**
Bosnia and Herzegovina					0.13	0.81		**0.94**
Brazil							0.78	**0.78**
British Indian Ocean Terr.					0.35			**0.35**
British Virgin Islands		0.55						**0.55**
Brunei Darussalam						0.12	0.27	**0.39**
Bulgaria		0.04			0.05	0.02	0.85	**0.95**
Burundi						0.25		**0.25**
Cambodia							0.66	**0.66**
Cameroon				0.25		0.36		**0.61**
Canada	0.85							**0.85**
Cayman Islands		0.45						**0.45**
Central African Republic					0.13	0.44		**0.57**
Chile					0.04	0.06	0.87	**0.97**
China					0.98	0.01		**0.99**
Christmas Island		0.46			0.39			**0.85**
Cocos Island	0.19	0.69			0.06			**0.94**

Country	Indiscrete	Population	Nonwoods	Plantation	Density	Literacy	Forests	Total r^2
Colombia			0.86		0.07			**0.92**
Comoros					0.18			**0.18**
Costa Rica					0.18		0.67	**0.85**
Cote D'Ivoire		0.15				0.35		**0.50**
Cuba					0.04	0.87		**0.92**
Czech Republic						0.89		**0.89**
Denmark		0.02			0.86		0.05	**0.94**
Dominica		0.10			0.57			**0.67**
Dominican Republic					0.34		0.35	**0.69**
East Timor					0.60			**0.60**
Ecuador	0.05						0.81	**0.86**
Egypt						0.77		**0.77**
El Salvador					0.51	0.15		**0.65**
Equatorial Guinea					0.66	0.06		**0.71**
Estonia						0.62		**0.62**
Ethiopia		0.16				0.46		**0.62**
Faeroe Islands	0.24	0.03			0.58			**0.85**
Falkland Is. (Malvinas)		0.34			0.36			**0.69**
Fiji				0.45				**0.45**
Finland	0.65							**0.65**
France							0.94	**0.94**
French Guiana							0.36	**0.36**
Germany					0.90	0.08		**0.98**
Ghana				0.22		0.41		**0.63**
Gibraltar					0.52	0.25		**0.77**
Greece							0.94	**0.94**
Greenland					0.46	0.09		**0.55**
Grenada					0.24			**0.24**
Guadeloupe						0.22		**0.22**
Guam					0.43	0.11		**0.54**
Guatemala		0.06			0.66	0.16		**0.88**
Guinea-Bissau					0.50			**0.50**
Guyana	0.53							**0.53**
Honduras						0.17		**0.17**
Hong Kong					0.69			**0.69**
Hungary							0.63	**0.63**
India							0.98	**0.98**
Indonesia				0.98	0.01			**0.99**
Iran			0.94					**0.94**
Iraq			0.17		0.36			**0.53**
Ireland					0.89			**0.89**
Israel		0.96						**0.96**
Italy	0.03					0.01	0.94	**0.98**

Country	Indiscrete	Population	Nonwoods	Plantation	Density	Literacy	Forests	Total r^2
Jamaica						0.18		**0.18**
Japan					0.94			**0.94**
Jordan					0.91			**0.91**
Kenya				0.05		0.69		**0.75**
Kiribati					0.58	0.12		**0.70**
Laos						0.21		**0.21**
Lebanon					0.68	0.06		**0.74**
Lithuania						0.80	0.16	**0.96**
Macau					0.53			**0.53**
Malawi		0.10		0.16		0.37	0.09	**0.72**
Malaysia				0.02		0.05	0.91	**0.97**
Maldives					0.51			**0.51**
Mali		0.31						**0.31**
Malta					0.10	0.64		**0.74**
Marshall Islands	0.12	0.68						**0.79**
Mauritania					0.63	0.09		**0.72**
Mauritius					0.88	0.06		**0.94**
Mexico							0.91	**0.91**
Micronesia		0.08			0.83			**0.90**
Montserrat					0.25			**0.25**
Morocco							0.71	**0.71**
Mozambique							0.22	**0.22**
Myanmar				0.14		0.65		**0.79**
Nauru		0.27			0.28			**0.55**
Nepal						0.66		**0.66**
Netherlands						0.93		**0.93**
New Zealand	0.75	0.06					0.07	**0.88**
Niger					0.29			**0.29**
Nigeria						0.22		**0.22**
Niue Island		0.12			0.45			**0.57**
Norfolk Island		0.26			0.42			**0.68**
Northern Mariana Is.		0.35				0.11		**0.45**
Norway							0.92	**0.92**
Oman		0.11				0.65		**0.76**
Pakistan		0.92						**0.92**
Palau		0.70			0.18	0.05		**0.93**
Panama							0.17	**0.17**
Papua New Guinea		0.12				0.35		**0.47**
Paraguay					0.21		0.73	**0.94**
Philippines				0.91				**0.91**
Pitcairn Is.	0.17	0.57			0.05			**0.80**
Poland							0.31	**0.31**
Portugal						0.91		**0.91**

Country	Indiscrete	Population	Nonwoods	Plantation	Density	Literacy	Forests	Total r^2
Qatar						0.69		**0.69**
Reunion					0.80			**0.80**
Romania		0.06			0.04	0.05	0.82	**0.96**
Rwanda		0.47						**0.47**
Saint Helena	0.16				0.65	0.04		**0.85**
Saint Kitts and Nevis		0.34			0.51			**0.86**
Saint Lucia					0.51			**0.51**
Saint Vincent/Grenadine					0.28			**0.28**
Sao Tome & Principe					0.30			**0.30**
Saudi Arabia					0.44	0.19		**0.63**
Seychelles					0.20			**0.20**
Singapore		0.75				0.12		**0.87**
Solomon Islands							0.36	**0.36**
South Africa						0.48		**0.48**
South Korea				0.00	0.01		0.99	**1.00**
Spain							0.97	**0.97**
Sudan					0.59			**0.59**
Suriname						0.90		**0.90**
Swaziland		0.06			0.86			**0.92**
Sweden	0.11				0.41			**0.53**
Switzerland						0.90		**0.90**
Syrian Arab Republic					0.20			**0.20**
Taiwan					0.99			**0.99**
Thailand					0.98			**0.98**
Tokelau Islands	0.15	0.63						**0.78**
Tunisia					0.96			**0.96**
Turkey			0.90			0.02		**0.92**
Tuvalu	0.16	0.52			0.17			**0.85**
Uganda						0.69		**0.69**
United Arab Emirates		0.55				0.29		**0.85**
United Kingdom							0.94	**0.94**
United States of America		0.94						**0.94**
Uruguay				0.85				**0.85**
Vanuatu					0.45			**0.45**
Viet Nam				0.93				**0.93**
Wake Island	0.18	0.61			0.06			**0.85**
Wallis and Futuna Is.	0.19				0.66			**0.85**
Yemen					0.35			**0.35**
Yugoslavia SFR		0.03				0.89		**0.92**
Zimbabwe							0.68	**0.68**

Appendix 2:

Paper and paperboard production – significant input variables

Numbers in the chart below indicate the partial r^2 values returned by SAS through stepwise regression, indicating the significant input variables and the relative importance of each variable to the overall correlation coefficient. Highlighted rows indicate countries where the data run was accepted.

Country	Indiscrete	Population	Nonwoods	Plantation	Density	Literacy	Forests	Total r^2
Albania					0.03	0.02	0.89	**0.95**
Algeria		0.19			0.33	0.26		**0.79**
Argentina					0.25	0.61		**0.85**
Australia							0.88	**0.88**
Austria		0.99				0.00	0.01	**1.00**
Bangladesh				0.95				**0.95**
Belgium-Luxembourg						0.67		**0.67**
Bhutan				0.36				**0.36**
Bosnia and Herzegovina					0.13	0.82		**0.95**
Brazil						0.95		**0.95**
Bulgaria		0.83				0.06		**0.89**
Canada		0.91						**0.91**
Chad							0.94	**0.94**
China			0.98	0.01	0.00	0.00		**1.00**
Colombia			0.96					**0.96**
Congo (Democratic Republic of)						0.18		**0.18**
Costa Rica					0.15		0.70	**0.85**
Cuba					0.03	0.82		**0.85**
Denmark		0.05			0.53	0.20		**0.78**
Ecuador							0.79	**0.79**
Egypt		0.86						**0.86**
El Salvador						0.67		**0.67**
Estonia						0.78	0.18	**0.96**
Ethiopia		0.66			0.26	0.03		**0.95**
Finland					0.96			**0.96**
France					0.01	0.01	0.96	**0.98**
Germany		0.83						**0.83**
Greece					0.12		0.79	**0.92**
Hong Kong					0.85			**0.85**
Hungary	0.26						0.59	**0.85**
India		0.99		0.00				**0.99**
Indonesia					0.99	0.01		**0.99**
Iran						0.23		**0.23**

Country	Indiscrete	Population	Nonwoods	Plantation	Density	Literacy	Forests	Total r^2
Israel		0.94			0.01			**0.95**
Italy	0.03					0.06	0.87	**0.96**
Jamaica					0.64	0.10		**0.74**
Japan					0.94			**0.94**
Jordan		0.87						**0.87**
Kenya						0.72		**0.72**
Kuwait		0.49						**0.49**
Latvia	0.81						0.17	**0.98**
Lebanon		0.06			0.68			**0.74**
Libya					0.13	0.67		**0.80**
Luxembourg						0.56		**0.56**
Macedonia						0.53		**0.53**
Malaysia				0.03		0.06	0.85	**0.95**
Mexico	0.10					0.77		**0.87**
Mongolia	0.79							**0.79**
Morocco						0.37	0.22	**0.59**
Mozambique							0.58	**0.58**
Myanmar				0.13		0.67		**0.80**
Nepal							0.76	**0.76**
Netherlands	0.96							**0.96**
New Zealand				0.14	0.53			**0.67**
Nigeria					0.27	0.47		**0.73**
North Korea					0.24	0.08	0.55	**0.86**
Norway							0.90	**0.90**
Pakistan					0.98			**0.98**
Panama						0.18		**0.18**
Paraguay					0.48		0.24	**0.72**
Peru							0.19	**0.19**
Philippines				0.87				**0.87**
Portugal					0.92			**0.92**
Romania					0.02	0.87		**0.90**
Saudi Arabia					0.55	0.30		**0.85**
Singapore		0.41				0.25		**0.66**
South Africa			0.12			0.74		**0.85**
South Korea				0.01	0.00		0.99	**1.00**
Spain			0.01			0.93		**0.94**
Sri Lanka						0.55		**0.55**
Sudan					0.08	0.04	0.77	**0.89**
Swaziland					0.94			**0.94**
Sweden					0.95			**0.95**
Switzerland					0.96			**0.96**
Syrian Arab Republic	0.52				0.07	0.19		**0.78**
Taiwan					0.98	0.01		**0.99**

Country	**Indiscrete**	**Population**	**Nonwoods**	**Plantation**	**Density**	**Literacy**	**Forests**	**Total r^2**
Tanzania, United Republic					0.08	0.76		**0.83**
Thailand					0.99			**0.99**
Tunisia					0.94	0.02		**0.96**
Turkey			0.90					**0.90**
Uganda				0.04		0.87		**0.91**
United Arab Emirates		0.33				0.31		**0.64**
United Kingdom		0.01				0.02	0.95	**0.97**
United States of America							0.97	**0.97**
Uruguay		0.86		0.03	0.02	0.05		**0.97**
Venezuela						0.60		**0.60**
Viet Nam					0.93			**0.93**
Yugoslavia SFR		0.05				0.87		**0.92**
Zimbabwe					0.15	0.77		**0.92**

Appendix 3:

Paper and paperboard recycling – significant input variables

Numbers in the chart below indicate the partial r^2 values returned by SAS through stepwise regression, indicating the significant input variables and the relative importance of each variable to the overall correlation coefficient. Highlighted rows indicate countries where the data run was accepted.

Country	Indiscrete	Population	Nonwoods	Plantation	Density	Literacy	Forests	Total r^2
Albania					0.26		0.59	**0.85**
Argentina							0.47	**0.47**
Australia					0.04		0.91	**0.95**
Austria		0.07					0.82	**0.90**
Bangladesh					0.84			**0.84**
Belgium		0.68						**0.68**
Belgium-Luxembourg		0.05			0.02	0.85		**0.93**
Brazil			0.07			0.77		**0.85**
Bulgaria		0.18				0.38		**0.56**
Canada					0.07		0.89	**0.96**
Chile						0.47		**0.47**
China					0.98			**0.98**
Colombia						0.53		**0.53**
Congo (Democratic Republic of)					0.75	0.05		**0.80**
Croatia						0.78		**0.78**
Czechoslovakia	0.49					0.42		**0.90**
Denmark							0.97	**0.97**
Ecuador	0.07						0.81	**0.88**
Egypt						0.56		**0.56**
El Salvador					0.18	0.26		**0.44**
Ethiopia					0.09	0.57		**0.67**
Finland					0.94			**0.94**
France							0.93	**0.93**
Germany		0.99					0.01	**1.00**
Greece					0.04		0.82	**0.86**
Hong Kong	0.57	0.12						**0.69**
Indonesia				0.74				**0.74**
Iran					0.09	0.75		**0.85**
Iraq	0.18							**0.18**
Ireland							0.73	**0.73**
Israel		0.90						**0.90**
Italy							0.71	**0.71**
Jamaica						0.34		**0.34**

Country	Indiscrete	Population	Nonwoods	Plantation	Density	Literacy	Forests	Total r^2
Japan					0.97			**0.97**
Kuwait		0.15			0.22	0.18		**0.55**
Latvia	0.68							**0.68**
Lebanon		0.33			0.54			**0.87**
Lithuania						0.77		**0.77**
Macau					0.88			**0.88**
Madagascar						0.14		**0.14**
Malaysia				0.83				**0.83**
Martinique						0.20		**0.20**
Mauritius					0.62	0.23		**0.85**
Mexico			0.58					**0.58**
Mongolia	0.19	0.34				0.35		**0.88**
Morocco					0.09	0.70		**0.79**
Netherlands					0.00		0.97	**0.98**
Nigeria						0.30		**0.30**
North Korea						0.01	0.98	**0.99**
Norway					0.10		0.86	**0.96**
Panama						0.21	0.42	**0.62**
Peru				0.37				**0.37**
Poland					0.36	0.05	0.51	**0.91**
Portugal		0.78						**0.78**
Romania		0.33						**0.33**
Saudi Arabia					0.07	0.81		**0.88**
Senegal		0.30			0.07	0.46		**0.83**
Singapore		0.37				0.14		**0.51**
South Africa			0.93					**0.93**
South Korea					0.21		0.66	**0.87**
Spain	0.96							**0.96**
Sri Lanka					0.66			**0.66**
Sweden							0.88	**0.88**
Switzerland							0.95	**0.95**
Taiwan			0.94					**0.94**
Thailand					0.86			**0.86**
Trinidad and Tobago		0.21				0.43		**0.64**
Turkey						0.68		**0.68**
United Kingdom		0.04					0.86	**0.90**
United States of America					0.00	0.01	0.99	**0.99**
Uruguay				0.51				**0.51**
Venezuela					0.18	0.67		**0.85**
Viet Nam				0.88				**0.88**
Yugoslavia SFR		0.03				0.87		**0.91**
Zimbabwe	0.04	0.04				0.83		**0.91**