Nutrient minimisation in the pulp and paper industry: an overview

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Abstract This paper reviews nutrient issues within the pulp and paper industry summarising: nitrogen and phosphorus cycles within treatment systems; sources of nutrients within pulping and papermaking processes; minimising nutrient discharge; new approaches to nutrient minimisation; and the impact of nutrients in the environment.

Pulp and paper industry wastewaters generally contain insufficient nitrogen and phosphorus to satisfy bacterial growth requirements. Nutrient limitation has been linked to operational problems such as sludge bulking and poor solids separation. Nutrients have been added in conventional wastewater treatment processes to ensure optimum treatment performance. Minimising the discharge of total nitrogen and phosphorus from a nutrient limited wastewater requires both optimised nutrient supplementation and effective removal of suspended solids from the treated wastewater. In an efficiently operated wastewater treatment system, the majority of the discharged nutrients are contained within the biomass. Effective solids separation then becomes the controlling step, and optimisation of secondary clarification is crucial.

Conventional practice is being challenged by the regulatory requirement to reduce nitrogen and phosphorus discharge. Two recent developments in pulp and paper wastewater treatment technologies can produce discharges low in nitrogen and phosphorus whilst operating under conventionally nutrient limited conditions: i) the nutrient limited BAS process (Biofilm-Activated Sludge) which combines biofilm and activated sludge technologies under nutrient limited conditions and ii) an activated sludge process based on the use of nitrogen-fixing bacteria. Aerated stabilisation basins often operate without nutrient addition, relying on settled biomass in the benthal zone feeding back soluble nutrients, or the fixation of atmospheric nitrogen. Thus effective nutrient minimisation strategies require a more detailed understanding of nutrient cycling and utilisation. Where it is not possible to meet discharge constraints with biological treatment alone, a tertiary treatment step may be required.

In setting nutrient control guidelines, consideration should be given to the nutrient limitations of the receiving environment, including other cumulative nutrient impacts on that environment. Whether an ecosystem is N or P limited should be integrated with wastewater treatment considerations in the further design and development of treatment technology and regulatory guidelines. End-of-pipe legislation alone cannot predict environmental effects related to nutrients and must be supplemented by an effects-based approach.

Keywords Nitrogen; nitrogen cycle; phosphorus; pulp and paper; wastewater

Introduction

Wastewater from the pulp and paper industry is considered to be nutrient limited with respect to conventional treatment technology, namely there is generally insufficient nitrogen and phosphorus contained within the wastewater to satisfy bacterial growth requirements. Micronutrients are generally present in sufficient quantities. Historically, nutrients have been added as part of the wastewater treatment process to ensure optimum treatment performance. Nutrient limitation has often been linked to operational problems, and controlling the addition and discharge of nutrients from nutrient limited wastewaters, whilst maintaining treatment performance, has proved to be a difficult process.

Conventional treatment technology design has focussed on the removal of organic carbon, suspended solids and toxicity. The introduction of processes such as ECF/TCF
bleaching, combined with the more comprehensive use of biological wastewater treatment, and a general drive towards water use reduction, has led to large decreases in biochemical oxygen demand, absorbable organic halide and resin acid discharges. The regulatory focus has now shifted from the acute toxicity effects of these components to chronic effects within the receiving environment, such as eutrophication due to anthropogenic nutrient input. An example is the directive from the HELCOM Ministerial meeting (1988) in which a 50% reduction in point and non-point sources of nitrogen and phosphorus to the Baltic was targeted. A subsequent report on progress towards this goal (Lääne et al., 2002) highlighted that lower reductions were achieved in countries where more advanced treatment systems were already in place. Large point sources such as discharges from the pulp and paper industry are also more readily targeted than diffuse non-point sources such as from agricultural operation. In order to better protect receiving environments and to direct wastewater treatment efforts more efficiently, the N:P ratio in the wastewater, the limiting elements in the receiving environment and/or other sources of nutrient input should be taken into account when determining discharge levels. A clearer understanding of these interactions must be gained in specific cases to ensure maximum protection for the environment without imposing unnecessarily stringent requirements for process improvements. The industry is being forced to meet much more stringent discharge standards without necessarily obtaining guidance from the regulators as to how to achieve those standards.

Reducing the loadings of nitrogen and phosphorus in the discharge presents a difficult problem for the industry as actual concentrations are often quite low. Before any minimisation strategy can be implemented, however, it is important to know the sources of nutrients within the process and their behaviour within a biological treatment system. If the majority of the discharged nitrogen and phosphorus is contained within biomass, rather than in the dissolved phase, nutrient minimisation depends on effective solids separation. Should the discharged nitrogen and phosphorus be mainly in the soluble phase, it is important to determine whether nutrient overdosing or benthic feedback is occurring, dependent on the treatment system used. Similarly, whilst a significant single source of nitrogen or phosphorus may be associated with a particular process stream, its removal from the whole mill waste stream, without knowledge of nutrient behaviour within the treatment system, may lead to detrimental effects in the treatment process. Further improvements in discharge quality may only be achieved by combining secondary and tertiary treatment.

The behaviour of nitrogen and phosphorus within both treatment systems and the receiving environment consists of a complex series of interactions. This paper reviews nutrient issues within the pulp and paper industry summarising: nitrogen and phosphorus cycles within treatment systems; sources of nutrients within pulping and papermaking processes; minimising nutrient discharge; new approaches to nutrient minimisation; and the impact of nutrients in the environment.

**Processes for nitrogen and phosphorus cycling**

**Bacterial nutrient requirements**

The major nutrients required for bacterial growth are C, H, O, N, P, and S, the basis of all microbial cells. Other elements required in smaller amounts, referred to as micronutrients, include Mg, K, Fe, Na, Ca, Mn, Zn, Cu, Co and Mo among others (Gostick, 1990). Actual concentrations of nutrients in an influent or treatment system however are not necessarily the concentrations available to the biomass.

Nitrogen is utilised in the synthesis of proteins, nucleic acids (DNA, RNA), and cell wall polymers. Both organic and inorganic forms of nitrogen can be utilised by bacteria. Assimilation of ammonium occurs by amination of a keto acid to form glutamic acid and transfer of the amino group to other keto acids thus forming other amino acids. Amino acids
are the building blocks of proteins and nucleic acids. When nitrate is used as a nitrogen source, it is first reduced to ammonia, and then converted to amino acids as described above. Phosphorus plays a key role in energy transfer within the cell, as well being utilised in the synthesis of nucleic acids, phospholipids and cell wall polymers.

**Nitrogen cycling**

Nitrogen is a key component of protoplasm, and can exist in a number of oxidation states: organic nitrogen (R-NH₃), −3; ammonia (NH₃), −3; nitrogen gas (N₂), 0; nitrous oxide (N₂O), +1; nitrite (NO₂⁻), +3 and nitrate (NO₃⁻), +5. Microorganisms are vital to the global nitrogen cycle, with a number of key redox reactions performed almost entirely by bacteria (Figure 1). Recycling of nitrogen on earth involves mostly the readily available forms, ammonia and nitrate.

The primary route of entry for the inert nitrogen gas into the biosphere is through bacterial nitrogen fixation, hence this process is of great ecological importance (Brock et al., 1984). Nitrogen fixation is defined as the incorporation of atmospheric nitrogen (N₂) as a source of nitrogen for bacterial growth. Nitrogen fixation is an anaerobic or microaerophilic process for aerobic, facultatively anaerobic, or anaerobic bacteria (Starr et al., 1981).

Nitrogen fixation is becoming increasingly recognised as a naturally occurring process in wastewater treatment systems (Gauthier et al., 2000; Gapes et al., 1999; Clark et al., 1997; Hynninen and Viljakainen, 1995; Bell et al., 1979). Identification of bacterial species using molecular biology techniques has shown that organisms historically associated with nitrogen fixation in treatment systems such as *Klebsiella* and *Azotobacter* species, whilst efficiently recovered using culturing techniques, are probably not numerically important microorganisms in nitrogen-fixing wastewater treatment systems (Reid et al., 2002b). Rather many of the organisms isolated from these systems are novel. There is significant potential in the treatment of nitrogen limited wastewaters to incorporate nitrogen fixation as a means of providing nitrogen for bacterial growth.

**Phosphorus cycling**

Unlike nitrogen, phosphorus does not have a volatile phase, and does not undergo oxidation and reduction (Brock et al., 1984). Although phosphate can be reduced to phosphite, hypophosphite and phosphine, its reduction potential is so low that it only rarely occurs in

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**Figure 1** Nitrogen transformations in nature (Brock et al., 1984)
natural environments. There is thus no biological means of incorporating phosphorus into a wastewater treatment system as there is for nitrogen. Phosphorus does however form highly insoluble precipitates with calcium, magnesium and iron which can remove the phosphorus from the soluble phase.

Organic phosphate compounds can be utilised as sources of phosphorus through the action of phosphatases which hydrolyse the organic phosphate ester (Brock et al., 1984). The phosphorus entering the system with the incoming wastewater, and that contained within sediments and/or decaying cells and able to be released back into the bulk liquor, therefore defines phosphorus availability within a wastewater treatment system.

A well recognised phenomenon occurring within wastewater treatment systems is that of “luxury uptake” of phosphorus or the “overplus” phenomenon (Levin and Saphiro, 1965), when more phosphorus is absorbed into the biomass than is required for cell growth. These concepts form the basis for biological phosphorus removal methods which are often utilised by municipal wastewater treatment plants (Saunamäki, 1994). The organisms involved in Enhanced Biological Phosphorus Removal (EBPR) have a complex physiology in which the formation and consumption of storage polymers (polyphosphate, glycogen, polyhydroxyalkonates) play a dominant role (van Loosdrecht et al., 1997). Biological phosphorus uptake requires conditions of alternating anaerobic and aerobic zones. Under anaerobic conditions, energy is released from stored phosphorus in the uptake of organic substrates and accumulation of PHA. More phosphorus than was originally released is then taken up again under aerobic conditions, and the stored PHA is utilised for energy and cell growth (Lee and Choi, 1999). EBPR processes are dependent on the selection of bacteria capable of storing large amounts of polyphosphate inside their cells. It is the authors’ experience that these processes may be occurring even in the treatment of low phosphorus wastewaters as found in the pulp and paper industry.

Nitrogen and phosphorus cycling from benthal deposits

It is often possible to operate pulp and paper aerated stabilisation basin (ASB) systems without supplemental nutrient addition and achieve effective treatment performance as feedback of soluble nutrients from benthal stabilisation of settled solids can be a significant source (Barkley and Sackellaes, 1987; Sackellaes et al., 1987; Bryant and Bauer, 1987; Bryant, 1995; Slade et al., 1999). Benthal stabilisation can be defined as a vertically integrated aerobic-anaerobic process whereby solids are stabilised in a sludge deposit by a combination of aerobic and anaerobic mechanisms, which results in the conversion of organic carbon and nitrogen to inorganic compounds and methane (Bryant and Rich, 1984).

Below the aerobic layer, anaerobic conditions prevail in which methane gas is evolved, as well as other products of anaerobic degradation. The anaerobic layer is not uniform and may reach its most active state between 2.5 and 5.1 cm below the mud-water interface (Filos and Molof, 1972). Ammonia and some of the less-reduced products from the anaerobic layers, such as organic acids, are transported upward to the aerobic layer by means of diffusion and advection induced by consolidation of the deposit. These products are either oxidised in the deposit (aerobic layer) or escape into the overlying water where they contribute to the soluble biochemical oxygen demand. Fresh solids joining the deposit at the top are decomposed by one or both of the mechanisms (oxidation or escape), depending on the rate of solids deposition. Benthal feedback of soluble BOD and nutrients from settled deposits of sludge has a major impact on the performance of heavily loaded lagoons, and the effect usually becomes greatest as the wastewater approaches the discharge pipe (Bryant, 1995).

Early observations suggested that phosphate release from sediments is regulated by both bacterial activity and the presence of adsorptive properties in the mud surface (Filos and
It was implied that as conditions first become anaerobic, the phosphate release was mainly from bacteria. Phosphate release into the overlying water was immediate, suggesting that it was a surface phenomenon. As conditions remained anoxic, anaerobic decomposition resulted in a destruction of the chemical complexes that existed in the aerobic layer, thus resulting in a freer exchange of nutrients between sediment and water. Phosphorus feedback has been correlated to increasing temperature (Holdren and Armstrong, 1980), high sediment oxygen demand (Chiaro and Burke, 1980), overlying DO below 1.5 mg/L, anoxic conditions (Kamp-Nielsen, 1974, 1975) and solubility parameters (Avnimelech et al., 1983). An increase in phosphorus feedback was also found to be independent of pH (Kamp-Nielsen, 1974, 1975), the overlying phosphorus level (Theis and McCabe, 1978) and the interstitial phosphorus concentration of the deep deposit layers (van Raaphorst and Brinkman, 1984). In active deposits the majority of phosphorus is in the biomass, and a significant amount may reside as precipitates of calcium, aluminium, and iron (Stumm and Stumm-Zollinger, 1972). The bacterial phosphorus content ranges from 1.5 to 3.8% by weight (Grady and Lim, 1980), and once solubilised, the conversion of organic phosphorus to orthophosphate may be rapid relative to other phosphorus reactions (Houng and Gloyna, 1984; Ferrara and Harleman, 1980; Fritz et al., 1979).

In contrast, it has been found that ammonia release does not follow the same complexities as phosphate release. Nevertheless studies suggest that a threefold increase in the ammonia release rate may occur under anaerobic conditions. The release of ammonia and the response to anoxic conditions appears to be slower, suggesting the important factor in ammonia release may be the adsorptive capacity of the aerobic layer (Filos and Molof, 1972). Nitrogen feedback has been correlated to high nitrogen content of benthal solids (Chiaro and Burke, 1980), increasing deposit depth (Fair et al., 1941), and overlying dissolved oxygen (DO) being below 1.5 mg/L.

Collins et al. (1986) found significant variation in net benthal nitrogen accumulation, with the largest ammonia release to overlying water occurring with high biomass production in summer. A slight overall accumulation of nitrogen occurred in summer with a net loss in winter. The primary reason for the trend was not influent variability, but rather the increase in effluent volatile solids. Also noted, from a series of tests, was that no appreciable fixation of atmospheric nitrogen occurred in the ponds (Collins et al., 1986) in contrast to findings by Clark et al. (1997) in which nitrogen fixation was shown to be important to the overall nitrogen budget.

Phosphorus accumulation remains consistent within the benthal deposit, but the effect may be more pronounced in the summer. The reduced winter accumulation is associated with the increased loss of effluent organic solids. Collins et al. concluded that the effect of effluent organic phosphorus in the overall mass balance has remained important and as expected, both nitrogen and phosphorus profiles displayed changes in the top layers and less change in the deeper portion (Collins et al., 1986).

Consistent with findings by Collins et al. (1986), Bryant and Bauer (1987) studied benthal feedback of soluble carbon and found that nutrients varied significantly with temperature, sludge type, and deposit volume. It was determined that phosphorus distribution was controlled by advection and biological uptake, while nitrogen feedback varied in a more complex manner. These factors can be extremely important to effluent quality and the performance of intermediate and later cells within an aerated stabilisation basin system.

**Sources of nutrients in pulping and papermaking**

Wood contains low quantities of nitrogen and phosphorus, therefore process waters from the pulp and paper industry mostly reflect this low nutrient status. Almost all nitrogen and phosphorus in wood feedstock dissolves in the pulping and bleaching processes and
eventually ends up in the effluents, solid waste or flue gases (Meloni, 1991). Phosphorus discharge from a paper mill is considerably less than that from a pulp mill and depending on the type of wood product, the discharge varies between 5 and 50 g/t (20 g/t average). Nitrogen discharges also vary widely depending on wood species and additives used, with discharges of 100–200 g/t being typical, however 1,000 g/t is not uncommon (Meloni, 1991). Numerous process additives contain nitrogen and phosphorus, including defoamers, water conditioners, scale inhibitors, biocides, slimicides, wet and dry strength additives and dyes/pigments (NCASI, 2001). The contribution of these additives to the overall nutrient budget is likely to be small. The chelating agents EDTA and DTPA may be of significance in biologically treated wastewaters.

Within the kraft process, two process streams have been identified as major contributors of specific nutrient species. The foul condensate stream contains significant quantities of ammonium as the foul condensate recovery area is a collection point for volatile components and ammonium nitrogen is a volatile gas under alkaline conditions. The D Stage of bleaching, as the first open acid stage of bleaching, is a purge point for phosphorus, mostly in the form of orthophosphate (Slade et al., 1999). These two major sources of nutrients should be readily available as a nutrient source for bacteria.

Minimising nutrient discharge
Minimising the discharge of total nitrogen and phosphorus from a nutrient limited wastewater requires both optimised nutrient supplementation and effective removal of suspended solids from the treated wastewater. In an efficiently operated wastewater treatment system, the majority of the discharged nutrients are contained within the biomass. Effective solids separation then becomes the controlling step, and optimisation of secondary clarification is crucial.

Optimising nutrient supplementation
Historically, the requirement for nutrient supplementation has been dependent on a number of factors including:

- nutrient balance and availability in the raw wastewater;
- the treatment process employed (high or low rate) and its efficiency;
- sludge age – the longer the sludge age, the more internal recycling of nutrients;
- biomass yield – the lower the yield, the lower the nutrient requirements;
- the influence of anaerobic growth – nutrient requirements for anaerobic stabilisation of carbon are much lower than for aerobic stabilisation;
- benthal interactions;
- solids settlability – sufficient nutrients are required to produce a high quality sludge;
- final discharge constraints will influence the supplementation strategy.

A survey of all the pulp and paper mills in Finland suggested that paper mill effluent requires dosing of both phosphorus and nitrogen, whereas pulp mill effluent only requires the addition of nitrogen since the amount of phosphorus dissolved from the wood in cooking and bleaching is generally sufficient (Meloni, 1991). Ammonia and phosphoric acid are commonly used as nutrient supplements, as well as urea, ammonium phosphate, diammonium phosphate and ammonium nitrate (NCASI, 2001).

Calculation of the specific biomass growth and hence nutrient requirements is a controversial area (Grau, 1991). An old “rule of thumb” for setting nutrient levels in activated sludge treatment has been a BOD:N:P ratio of 100:5:1 (Springer, 1993). In practice, it has been found that the nitrogen and phosphorus requirement in relation to BOD is not always as great as is implied by the above ratio (Saunamäki, 1994). For example, a ratio of 100:3.5:0.6 was found to be appropriate if nutrient dosage to the activated sludge process...
were optimised (Möbius, 1991). As a general rule, the 100(P/BOD) value should not fall below 0.4 for long periods and the BOD:N ratio is acceptable at 100:(2.5–4.5).

Very close control of nutrient supplementation, and therefore nutrient discharge, requires on-line monitoring of flow and organic strength, a knowledge of system nutrient requirements, and potentially feedback control of effluent nutrient species. Two recent developments in wastewater treatment technology have challenged conventional practice and have exploited certain microorganisms’ ability to adapt to low nutrient environments. These systems operate with minimal nutrient addition achieving high discharge quality with respect to both organic and nutrient loadings to the environment.

**Nutrient limited BAS process.** The nutrient limited Biofilm Activated Sludge (BAS) process has been developed to lower sludge production and improve sludge quality in the activated sludge process. It consists of sequential moving bed biofilm and activated sludge technology in which the MBBR is operated under strict nutrient limitation (Welander et al., 2001). Nutrient limitation in the biofilm process results in the production of extracellular polysaccharide slime which is then degraded in the following activated sludge process. The process can achieve excellent treatment performance, very low sludge yields and low nutrient discharge.

**N-ViroTech® process.** N-ViroTech® is a novel treatment process designed to treat nitrogen limited wastewaters using communities of nitrogen fixing bacteria (Slade et al., 2001, 2003, 2004; Reid et al., 2002a, b; Gapes et al., 1999). The process relies on manipulation of growth conditions within the biological system to maintain a nitrogen-fixing population whilst achieving wastewater treatment goals. This technology avoids the need for controlled nutrient addition to wastewaters which exhibit varying organic loads, as the bacteria only fix the nitrogen required for growth. Very low dissolved nitrogen, and potentially low phosphorus levels can be achieved in the treated wastewater. Through eliminating nitrogen addition, and minimising phosphorus addition, it has been estimated that between 25% and 35% of the treatment operating costs can be saved (Slade et al., 2004).

**Effects of nutrient limitation**

Nutrient deficiency can have a dramatic effect on wastewater treatment plant performance, typically manifesting itself as a reduction in BOD removal efficiency leading to high effluent BOD. As the microorganisms are unable to obtain sufficient nutrients for enzymatic and cellular activities, resulting in limitation of their growth, their ability to take up and metabolise organic pollutants is reduced (Gostick, 1990). Nutrient deficiency may also impact on the microbial ecology of the biomass, resulting in poor settling and possibly changing species profile. The type and magnitude of these effects is dependent on the type of industrial wastewater (Gostick, 1990; Grau, 1991). It has been recognised that not only nutrient deficiency, but also other factors can influence settlability, namely substrate composition and concentration, DO, temperature and pH (Grau, 1991).

Nutrient limitation can affect biomass settlability in two ways. Firstly, it can result in the growth of filamentous organisms, which can out-compete floc forming organisms due to their increased surface area allowing preferential adsorption of available nutrients. Secondly, particularly in response to phosphorus limitation, bacteria can produce extracellular polysaccharide substances (EPS or slime) as a means of utilising excess carbon, without producing new bacterial cells. High levels of slime result in low density flocs which settle poorly. Nutrient deficiency may indeed lead to an increase in discharged nitrogen and phosphorus as settlability decreases and the discharge of suspended solids increases.
**Tertiary treatment**
Where it is not possible to meet regulatory constraints with biological treatment alone, a tertiary treatment step may be required. Chemical precipitation of phosphorus is the most common tertiary treatment in the pulp and paper industry, and wetlands are often used for nitrogen removal from municipal wastewaters. Tertiary treatment of high volume wastewaters is expensive, and produces a further waste stream for disposal. Consideration of the real impact of the nutrient load on the environment should be made before tertiary treatment is stipulated.

**The impact of nutrients in the environment**
Eutrophication has been observed to impact up to 60% of streams and lakes in some countries. Effects of nutrient enrichment in pulp and paper receiving environments have been observed for many decades. Bothwell (1992) describes blooms of benthic diatoms in the Thompson River (BC, Canada) in the 1970s that were so dense that they totally obscured the topography of the river over a 20–40 km reach.

When considering the discharge of pulp and paper wastewaters to receiving environments, regulations initially targeted BOD and acute lethality of pulp and paper effluents, with organochlorines and reproductive dysfunction in fishes following. Though some unease continues to exist regarding the effects of endocrine disrupting compounds, process and treatment improvements have generally eliminated issues of acute toxicity and persistent organic pollutants. Despite the fact that eutrophication influences a substantial proportion of all freshwater ecosystems, nutrient effects on aquatic environments influenced by pulp and paper mill effluents have not received widespread scientific scrutiny, and only more recently have been the focus of regulatory concern. Nutrient impacts on aquatic ecosystems may have become more apparent as other effects have diminished.

The reduction of inhibitory or toxic effects of pulp and paper mill effluents on algae can result in increased primary productivity due to nutrient enrichment (Podemski and Culp, 1996). The effects of nutrients are not only dependent on inorganic nutrient content in the effluent, but also depend strongly on the hydrological and limnological nature of the system influenced. A central dogma of limnology is that primary productivity in most aquatic environments is limited either by N or by P (dissolved inorganic N and dissolved reactive P). This can be estimated using N:P ratios (greater than 20:1 being P limited and less than 10:1 being N limited) or empirically by the addition of nutrients to recipient water and observing primary productivity. Extensive investigation in the Athabasca and Peace River basins of western Canada (33 sites) have shown a mixture of P limited, N limited, N and P limited and non-limited reaches of river (Scrimgeour and Chambers, 2000). Epilithic chlorophyll a was strongly related to the presence of pulp mills and sewage treatment plants. Such nutrient limitations can also vary seasonally with flow (Dubre et al., 1997). Though a significant proportion of organic N can be mineralised by heterotrophs, the considerable length of time required to produce inorganic nitrogen would suggest that immediate effects in lotic environments due to mineralisation are unlikely and that the inorganic nitrogen is of greatest concern (Priha and Langi, 2000). Similarly, 90% of total phosphorus (only 20% was dissolved reactive P) can become bioavailable through biological degradation given an appropriate residence time (Priha, 1994).

Reduced light penetration and large quantities of organic carbon have also been observed to result in large increases in heterotrophic biomass, including algae that are facultative heterotrophs (Amblard et al., 1990). Davis et al. (1988) also noted a shift to heterotrophy downstream of a mill discharge and attributed this to changes in light attenuation. As with autotrophs, heterotrophic biofilms are also typically limited either by nitrogen or phosphorus where organic carbon is abundant (Mohamed et al., 1998). This
shift to increased heterotrophic communities would contribute greatly to summertime oxygen sags that are still observed to occur in certain lotic systems such as the Tarawera River in New Zealand.

Increased algal and bacterial productivity has clearly demonstrated “bottom-up effects” on other biota. Where toxicity does not occur, increased growth in invertebrates and invertebrate biomass (Dubé and Culp, 1996; Dubé et al., 1997) is observed but usually accompanied by decreases in invertebrate diversity. Effluent exposure also has well-established effects on fish productivity (Hall et al., 1991). Out of 53 fish surveys performed as a part of the Canadian Environmental Effects Monitoring (EEM) program for pulp and paper mills the distributions of condition factor and liver size was skewed towards increases, likely reflecting greater energy storage due to increased system productivity (Munkittrick et al., 2002). Though not typically measured, it is the authors’ experience that fish abundance and biomass (as judged by catch per unit effort) is generally dramatically greater downstream of pulp and paper effluent discharges.

Though not yet apparent in the literature, nutrient enrichment and other contributing factors to bacterial and algal productivity such as seasonality and effluent colour will pose the greatest environmental challenge for the industry into the future. Nutrient discharge guidelines will in many cases not succeed at preventing environmental impairment unless they are tailored to the receiving environment on a case-by-case basis. End-of-pipe legislation alone cannot predict environmental effects and must be supplemented by an effects-based approach such as the Canadian EEM program. As with other environmental challenges overcome by the industry, development of appropriate technological and management solutions will require the cooperation and collaborations of scientists from various disciplines, particularly limnologists and waste treatment scientists, with industry and managers.

Conclusions
Minimising nutrient discharge from nutrient limited wastewaters, where nutrient supplementation is often practised, requires consideration of many factors. Nutrient inputs to the system must be optimised, and this can be achieved by:

- Understanding the bacterial nutrient requirements which will vary with nutrient balance and availability in the raw wastewater; the treatment process employed (high or low rate) and its efficiency; sludge age; biomass yield; the influence of anaerobic growth; benthal interactions; solids settlability; and final discharge constraints;
- Implementing close control of nutrient addition combining on-line monitoring of flow and organic strength, a knowledge of system nutrient requirements, and potentially feedback control of effluent nutrient species;
- Optimising secondary clarification to achieve maximum solids separation;
- Adopting new technologies designed to operate under nutrient limited conditions;
- Implementing tertiary treatment where nutrient limits cannot be achieved by biological treatment alone.

For all treatment processes, as residual dissolved nutrient concentrations are lowered, the overall nitrogen and phosphorus discharge is governed by the suspended biomass. Absent from current nutrient control guidelines is consideration of the nutrient limitations of the receiving environment, including other cumulative nutrient impacts on that environment. Consideration of whether an ecosystem is N or P limited should be integrated with wastewater treatment considerations in the further design and development of treatment technology and regulatory guidelines. End-of-pipe legislation alone cannot predict environmental effects and must be supplemented by an effects-based approach.
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