

**MEAT AND BONE MEAL AS A NITROGEN AND
PHOSPHORUS FERTILIZER FOR RYEGRASS**

PRIIT TAMMEORG
MASTER'S THESIS
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Tiivistelmä — Referat — Abstract <p>Meat and bone meal (MBM) is a valuable co-product of the rendering industry. Its feed and fertilizer uses were restricted in the EU in 2002 as a result of the occurrence of BSE crisis. Consequently, MBM was land filled, incinerated or used as an alternative fuel in cement production. The re-allowance of the fertilizer use of MBM in the EU since spring 2006 together with the rising prices of industrial nitrogen and phosphorus fertilizers have resulted in amplified research and use of MBM as a fertilizer. Additionally, growing consciousness of both finiteness of resources and deteriorating environmental effects of the artificial fertilizer use have contributed to growing popularity of nutrient recycling. The fertilizer effect and the nutrient uptake efficiencies of the Finnish MBM (N-P-K-Ca 8–6-0.5-15%) compared to mineral counterparts were tested for in present study. Additionally, the fertilizer effect of MBM in mixture with two potassium fertilizers was tested for.</p> <p>A greenhouse experiment with ryegrass (<i>Lolium multiflorum</i>) fertilized with five fertilizers (MBM, mineral fertilizers Y4PK and NK, two mixtures of MBM and potassium fertilizers) was conducted from 2007 to 2008 in Department of Agricultural Sciences greenhouses in University of Helsinki, Finland. Each of the fertilizers was applied on three nitrogen levels (80, 160 and 240 kg N ha⁻¹). Four additional reference treatments (0 kg N ha⁻¹ fertilizer, PK I, PK II and PK III) were included. Six cuts of ryegrass were cut and the yields were recorded. Post-harvest plant and soil analyses were conducted.</p> <p>MBM was shown to be a highly effective N and P fertilizer with fertilizer effect similar or even longer lasting than artificial Y4PK fertilizer. Additionally, unlike highest application levels of mineral fertilizer Y4PK and NK, meat and bone meal treatments did not lower the pH level of the soil. Therefore, it can be concluded that the relatively high Ca content of MBM is useful in preventing further costs for liming the soil. The nutrient uptake efficiencies of MBM were generally somewhat lower than for mineral counterparts. That could be partly attributable to possible immobilization of MBM-N to soil and partly to lower readily plant-available P content of MBM than mineral fertilizers. However, as significant amount of MBM-P is still available for following years, it is justified to use MBM only once in a crop rotation. That makes MBM an especially effective complementary N and P fertilizer for organic farming, where most of the nitrogen need in crop rotation is covered with legumes and manure.</p> <p>The fertilizing potential for mixture of MBM and K fertilizers was shown to be rather high. However, the lack of affordable potassium sources suitable for organic farming is a recognized challenge. Additional research is needed for convalescing MBM as NPK fertilizer.</p>			
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1. Introduction

1.1. Nitrogen and Phosphorus Fertilizers

Mineral nitrogen fertilizers

Nitrogen is essential for many important functions in plant compounds, as it is crucial part of amino acids, enzymes, nucleic acids and chlorophyll. Nitrogen supply is, among other things, critical for root growth and development, uptake of other nutrients and the use of carbohydrate in plants. Generally, nitrogen contributes 2.5-4 % of healthy plant foliage, depending on the age of the plant or whether it is a legume or not.

Vast amounts of nitrogen can be found in the atmosphere (gaseous dinitrogen N_2 contributes approximately 78% of the atmosphere). Unfortunately, only a minor part of this virtually limitless reservoir can be directly used by plants, due to exceptionally strong triple bond between the two nitrogen atoms. As plant roots generally take up nitrogen from the soil solution as nitrates (NO_3^-) and NH_4^+ ions (Figure 1.1.), a mechanism to turn gaseous dinitrogen into the abovementioned ions is needed (Brady & Weil, 2002, p. 544-547).

Natural mechanisms for transitioning gaseous nitrogen into plant-usable reactive nitrogen (Nr) encompass N fixation by symbiotic and non-symbiotic microorganisms and to some extent, also lightning. The symbiotic N fixation includes symbiosis between nitrogen fixing bacteria (i.e. from genera *Rhizobium* and *Bradyrhizobium*) and plants (mostly legumes, but also numerous non-legumes are known). Additionally, certain free-living microorganisms (i.e. bacteria from genera *Azotobacter* and *Clostridium*) can be credited for non-symbiotic nitrogen fixation, as they are not directly connected to higher plants (Brady & Weil, 2002, p. 564-572). In addition to freely living microorganisms in soil, James (2000) suggests, that bacteria living in plant itself, “endophytic diazotrophs”, that colonize the apoplast and dead plant cells instead of living within healthy host cells, are fixing notable amounts of Nr.

Another small group of bacteria (i.e. from genera *Pseudomonas*, *Bacillus* and *Micrococcus*) can transform (denitrify) Nr back to N_2 and those two opposite processes (denitrification and nitrification), are reported to have been approximately equal in the preindustrial era (Ayers *et al.* 1994).

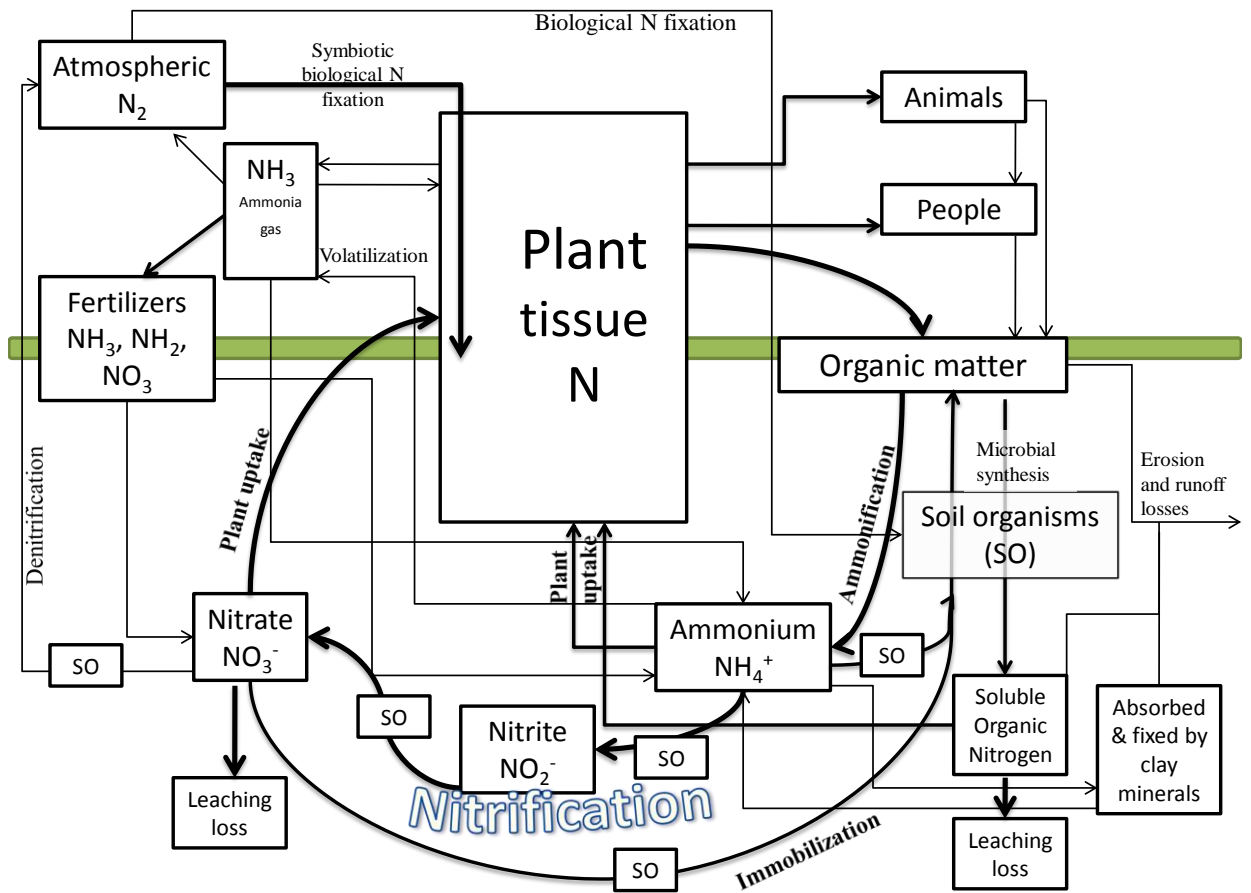


Figure 1.1. The nitrogen cycle in a soil-plant system. The primary cycle, in which organic nitrogen is mineralized, then taken up by plants and eventually organic nitrogen is returned to the soil as plant residues, is represented by heavy arrows. (Brady & Weil 2002:547, revised).

In the beginning of the 20th century, the mankind's growing demand for food and fibre was increasingly harder to be met using only the traditional methods (crop rotations including leguminous species, usage of leguminous green manures and recycling of organic wastes) and alternatives were looked for. A solution was found in 1913, when the chemical process to convert atmospheric N_2 to NH_3 was invented by F. Haber and developed further by C. Bosch (Galloway & Cowling, 2002, Galloway *et al.* 2002).

The invention and implementation of Haber-Bosch process in the 1910's made large scale ammonia production possible, resulting in rapid increase in the use of reactive nitrogen. The production of nitrogenous fertilizers started mushrooming after World War II; resulting in over 40% of the world's current dietary fibre production relying to the Haber-Bosch synthesis of ammonia (Smil 2002). According to FAO, the world's total nitrogen fertilizer production was 96 Mt in 2006, and recent developments

suggest a continuous increase in consumption of nitrogen (1.8% annually until 2011) (FAOSTAT 2009, Maene 2007).

Mineral phosphorus fertilizers

Phosphorus is another essential component of the living cell. As well as it is part of the high-energy phosphate group (ATP) that drives most energy requiring biochemical processes in organisms, it is also indispensable component of DNA and of RNA. Nevertheless, the total phosphorus content of healthy leaf tissue is rather low, generally comprising only 0.2-0.4% of the dry matter. As a rule, plant roots absorb phosphorus dissolved in the soil solution as phosphate ions (HPO_4^{-2} and H_2PO_4^-), but additionally, some soluble organic phosphorus compounds are also taken up (Figure 1.2.) (Brady & Weil 2002, p. 592-602).

Similarly to nitrogen, gargantuan stocks of phosphorus are unreachable for plants as well as the extractive capabilities of the mankind. Enormous amounts of phosphorus can be found from marine and freshwater sediments, whereas metamorphic and volcanic rocks contain considerably smaller mass of it. By far the largest reservoir of P potentially accessible by plants can be found in soils (Smil 2000). Brady and Weil (2002, p. 594) define three main problems of phosphorus in soil fertility: low total phosphorus level of soils, common unavailability of the phosphorus compounds and fixation of soluble sources of P.

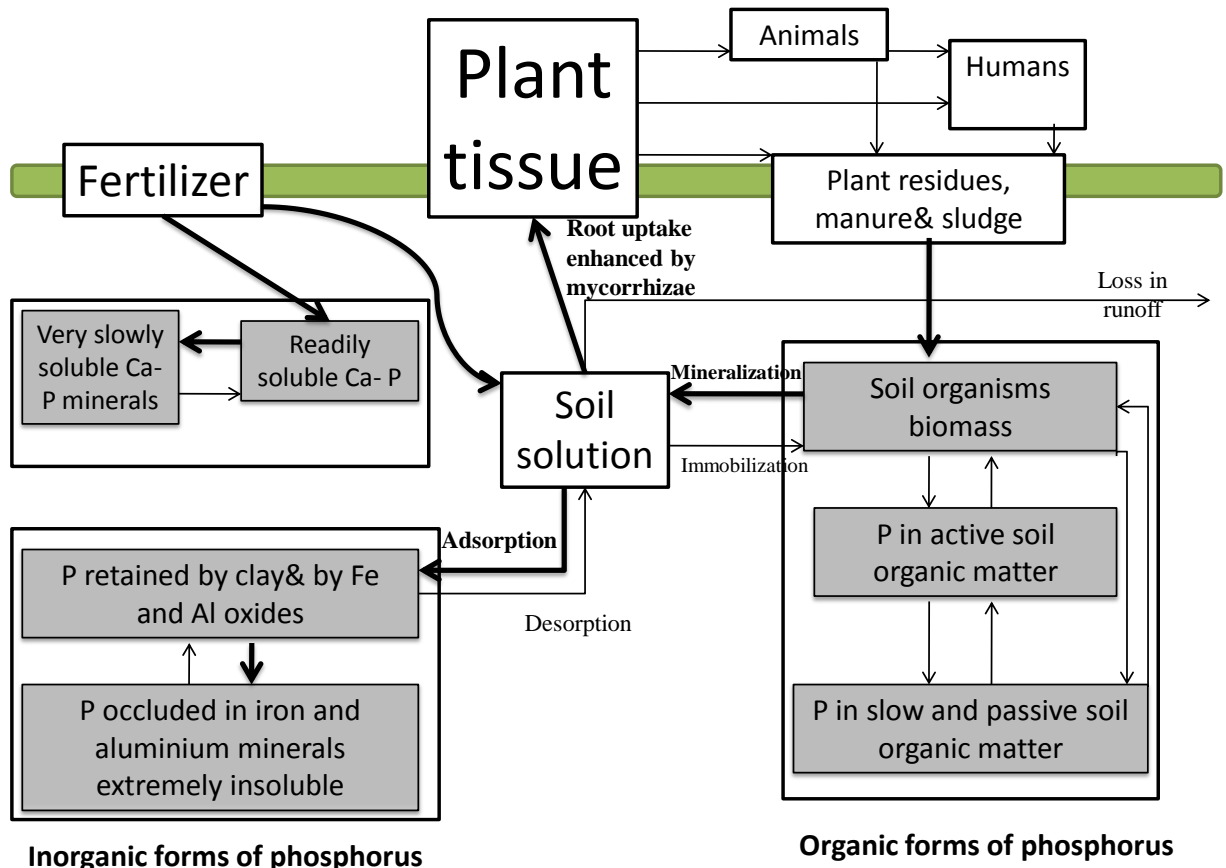


Figure 1.2. The phosphorus cycle in soils. The boxes represent pools of different forms of phosphorus in the cycle, while the arrows represent translocations and transformations among these pools. Note that due to phosphorus lacking the gaseous form and strong adsorption by mineral surfaces, generally no P is lost from soil in gaseous forms or via leaching (Brady & Weil 2002, p.602, revised).

By the mid-19th century, the long-established methods- using natural phosphorus levels found in soils together with locally available organic matter (manure and human excreta) - were insufficient to fill the needs of increasing population's demand for food. Solutions were found by using guano- bird excreta originating from coastal cliffs of Peru- and mining phosphorus-containing rocks (Neset *et al.* 2008). In the beginning of 20th century, the importance of latter increased significantly as the guano stocks were declining and the long distance transport turned unfeasible. The market for mineral fertilizers developed swiftly, as phosphate rock was being seen as an unlimited source of concentrated phosphorus (Cordell, 2009). Processed mineral fertilizers, like ordinary superphosphate (OSP), contained an order of magnitude more phosphorus than the commonly recycled P-rich manures (depending on the treated mineral, the OSP contained between 7–10% of available P). Furthermore, treating the phosphate rock with phosphoric acid increased the share of soluble P two to three times above the level

in OSP, and the compound generally known as triple superphosphate (TSP) contains 20% phosphorus. Abovementioned processes played crucial roles in increase of popularity of mineral P fertilizers (Smil, 2000).

In addition to vast phosphate deposits in the United States, new enormous stocks were discovered from Morocco (marine deposits) and Kola Peninsula (high grade apatite mines) between the world wars. Since the above-mentioned discoveries, there have been only two new sizeable findings of phosphate deposits- from China and Jordan- but until 1990-s, there was an exponential growth of the global P extraction. It has been calculated, that between 1850 and 2000, the Earth's agricultural soils received approximately 550 Mt P, an equivalent of almost 10% of arable soils' total phosphorus content (Smil 2000). According to FAOSTAT, the world's annual consumption of phosphate fertilizers from 1961 to 2002 had increased threefold (from 10.9 Mt to 33.5 Mt) whereas the price for farmers had risen over 150 times (FAOSTAT 2009).

According to FAO (2006), the phosphate can well be currently the most critical raw material in the world. Global reserves (actual and probable) with more than 20 percent P_2O_5 content are reported to be in the range of 30–40 000 million tonnes. The long history of excessive P application in developed world has resulted in present situation, where the critical levels have exceeded and the demand for mineral phosphorus is decreasing. The developing world, on the contrary, is expected to have steady increase in demand for phosphorus fertilizers (majority of the anticipated global increase (3% annually by 2011) is expected from Asia and Africa. (FAO 2006, Maene 2007).

In the present day, mankind is effectively addicted to phosphorus-containing rocks. Yet it should be noted that phosphate rock is a non-renewable resource and the depletion of current economically exploitable deposits can be estimated at somewhere from 60 to 130 years, the inevitable Peak Phosphorus being predicted at year 2033 (Steen 1998, Cordell 2009). Furthermore, it is predicted, that the population growth and change in diets bring along about 50-100% higher demand for phosphorus by 2050 (Steen 1998). Additionally, the geopolitical aspect should be taken into account as the world's remaining phosphate rock reserves are under the control of a handful of countries, including China, the US and Morocco (Steen 1998, FAO 2006).

Environmental and human health issues related to mineral nitrogen fertilizer use

Over past two hundred years, the global human population increased from 0.85 billion to 6.2 billion and the last population doubling up to date took only 40 years (Smil 2001,

FAO 2006). In spite of some efforts to slow the growth rate, the global population is expected to reach 7 billion early in 2012, up from the current 6.8 billion, and surpass 9 billion people by 2050 (UN 2009). The population increase during the next two decades will take place almost entirely in 93 developing countries. With an annual growth rate of 1.5 percent, there will be 1.5 billion more people by 2020, half of them urban. This increase is equivalent to the entire population of the developed countries (FAO 2006). The population growth at such a tremendous pace brings inevitably along several environmental issues, among them severe fertilizer-related ones.

On the global scale, soil fertility depletion is far more extensive than is soil fertility improvement. Depletion of soil nutrients is caused mainly by negative nutrient balances, faulty nutrient management strategies and a lack of resources for investment in soil-fertility-enhancing inputs. The constant removal of crop produce without sufficient replenishment of plant nutrients exported by the crop causes a steady decline in soil fertility. Additionally, low crop yields resulting from nutrient depletion force farmers to cultivate land under forests or marginal soils that are subject to erosion or desertification, resulting in land degradation (FAO 2006). Moreover, large areas of soils in the tropics are essentially poor in soil nutrients and suffer from problems of acidity, Al toxicity, alkalinity and salinity. Organic recycling can solve the problem just to some extent as the biomass produced on poor soils is itself exceedingly poor in essential plant nutrients. Such soils can be made productive with appropriate amendments and a basic application of plant nutrients (FAO 2006).

On the other hand, excessive nutrient amount applied to soils cause severe problems, as well. Currently, the mankind creates total of ~165 Mt reactive nitrogen annually. This amount is about twice the amount of reactive N created by biological nitrogen fixation in natural terrestrial ecosystems (~ 90 Mt N annually) (Galloway and Gowling 2002). During only a century, from 1890 to 1990, the NH_3 emissions increased from 9 to 43 Mt N annually, as a consequence of food production; NO emissions increased from 7 to 36 Mt N yr^{-1} from both energy and food production. The increased emissions resulted in widespread distribution of reactive nitrogen to downwind ecosystems. Transfer of Nr to marine systems also increased. By 1990, atmospheric N deposition to marine regions had increased to 27 Mt N yr^{-1} and riverine dissolved inorganic nitrogen fluxes to the coastal ocean had increased to 20 Mt N yr^{-1} (Galloway and Gowling 2002). Anyhow, by 1998, a tendency of decrease of gaseous nitrogen emissions (10-15%) in the Europe was reported, largely because of reductions in animal production in the former Soviet Union (Erisman *et al.* 2003). According to Antikainen

et al. (2008), the same applies to Finland's nitrogen emissions. After peaking in 1980's, a rather steady decrease due the localization of fertilization and reduction of fertilizer amounts is anticipated. Nevertheless, a notable nitrogen surplus in Finnish agricultural soils remained- the annual average surplus being 29 kg ha⁻¹ in 1995-1999 (Antikainen *et al.* 2005). The same applies to Poland, nitrogen surplus averaged at 45 kg ha⁻¹ in 2002-2004, whereas great majority (48.3%) of N inputs originated from mineral fertilizers (Kopinski *et al.* 2006).

Human-induced increases of Nr have a wide variety of both beneficial as well as harmful changes in the health and welfare of ecosystems and people. Whether the effects are beneficial or detrimental is often determined by the magnitude of the Nr flux (Galloway *et al.* 2000).

When it comes to environmental effects of human-created Nr, in Nr limited ecosystems, high rates of reactive nitrogen input often have harmful impacts to the environment. For instance, acidification, losses of biodiversity both in terrestrial as well as in aquatic ecosystems, eutrophication and invasion by N-loving weeds (Matson *et al.* 2002, Rabalais, 2002), and changes in composition and diversity of beneficial soil organisms that alter ecosystem functions (Matson *et al.* 2002) can all be caused by excessive Nr load. Eutrophication has often been related only to P emissions, but as Paerl (2009) points out, single nutrient input reductions (either N or P) are not to be expected to be effective in diminishing the eutrophication effect. He strongly stresses the need for a holistic approach- only when the entire freshwater- marine continuum, and both nitrogen and phosphorus inputs, are taken into account, the eutrophication could be controlled (Paerl 2009).

Increased Nr has a remarkable effect to air quality and global climate, as well. As NO_x emissions increase the tropospheric ozone, they can give rise to ozone-induced injury to crop, forest, and natural ecosystems, which would be a predisposition to the damage caused by pathogens and insects. Additionally, the increased emissions of N₂O from terrestrial and aquatic ecosystems can result in significant changes in global climate as the global warming potential of N₂O is over 200 times greater than that of CO₂ (Wolfe and Patz, 2002). Furthermore, long-distance transport of Nr results in harmful effects in regions distant from emission sources, as fossil fuel combustion is the largest anthropogenic source of NO (Galloway *et al.* 2002, Matson *et al.* 2002).

On the subject of Nr implications concerning human health, the most obvious of the beneficial effects are increased nutritional quality of available foods, together with increasing global and regional food supplies. Negative factors contributing to human

health effects may include a direct causal factor (e.g. NO₂, which increases susceptibility to both viral and bacterial respiratory infections) as well as the exposure medium (e.g. water, air) and the susceptibility of a specific human population (e.g. asthmatics, those from the developing countries) (Wolfe and Patz, 2002). Additionally, exposures to Nr-related health risks may occur through water pollution, which can cause methemoglobinemia, exposure to toxic *Pfiesteria* and eutrophication. Finally, Nr-related health effects may be indirectly realized *via* global atmospheric exposures. (Wolfe and Patz, 2002).

Environmental and human health issues related to mineral phosphorus fertilizer use

In 2000, the global crop harvest assimilated approximately 12 Mt phosphorus annually, which is twelve times more than in 1800. Similarly, the amount of recycled organic matter has increased from 0.5 to more than 6 Mt annually, but the greatest change has taken place with inorganic P fertilizer applications- from zero to 15 Mt. Consequently, losses of phosphorus from soils to air and waters have boosted from natural level of 10 Mt year⁻¹ to 30 Mt in 2000, for the most part because human actions have roughly tripled the rate at which the nutrient reaches the streams (Smil 2000).

Nevertheless, significant differences in phosphorus management strategies exist between different regions and even countries. As in Poland, in 2002-2004, the annual P balance was slightly positive (2.8 kg ha⁻¹) (Kopinski *et al.* 2006), the surplus in China in 2004 was notably greater (14.7 kg ha⁻¹) (Chen M. *et al.* 2008). In Finland, mean annual surplus of phosphorus during 1995-1999, was 12.7 kg ha⁻¹ (Antikainen *et al.* 2005), as the P input to agricultural soils had steadily decreased after peaking in 1970. A great deal of total phosphorus emissions to waters originates from agriculture- more than 80% in United States (Carpenter *et al.* 1998). Kronvang *et al.* (2007) report that phosphorus losses from agricultural areas to water in case of macro-catchments in Europe could be as high as up to 6.0 kg P ha⁻¹ year⁻¹. Additionally, Chen M. *et al.* (2008) state that mineral phosphorus fertilizer application, together with livestock production, were the two most prevailing contributors to P emissions to surface water in China in 2004 (accounting for 51.2% and 39.1% of the total load respectively). Smil (2000) stresses that the main pathway of P reaching to waterways is due to soil erosion.

Phosphorus added from soil to aquatic systems, differently from compounds originating from the cycling of nitrogen (e.g., nitrates and ammonia), is not toxic to fish, livestock or humans, except in very high concentrations (Smil 2000, Brady and Weil,

2002, p. 595). Nonetheless, too much or too little phosphorus can have severe and extensive negative impacts on environmental quality. The most prevalent environmental problems related to soil phosphorus are land degradation caused by too little available phosphorus and accelerated eutrophication of waters caused by too much (Brady and Weil, 2002, p. 595).

Similarly to nitrogen, the phosphorus deficiency is more widespread in the global scale than surplus. By estimate, of up to two billion hectares of land worldwide suffer from soils low P-content. The phosphorus deficiency is primarily found in low-income countries, where mineral fertilizers are too expensive to afford for most farmers (Brady and Weil, 2002, p. 595). As sufficient amounts of P in plants also increase the response to applications of N and K, phosphorus deficiencies are commonly marked by overall stunting, rather than specific signs. In addition to that, low P supply reduces the rate of nitrogen biological fixation and maintenance of soil organic matter, hence lowering the soil's water-holding capacity and increasing erosion (Smil 1999a).

Then again, excessive mineral phosphorus applications may result in severe environmental problems, as accelerated eutrophication and algal blooms of *Pfiesteria*. Eutrophication is caused mainly by nitrogen, phosphorus and carbon, but as P is the most biomass growth limiting nutrient in the fresh water environment, it deserves most consideration (EFMA 2000, Smil 2000). Besides, a single atom of P supports, by the Redfield's ratio, the production of as much phytomass as 16 atoms of N and 106 atoms of C (Redfield, 1958). Environmentally, perhaps the most apparent consequence of eutrophication is the increased growth of aquatic weeds and algae, decomposition of which can cause oxygen shortages, and consequently, fish kills (Carpenter *et al.* 1998, Smil, 2000). Fish species, whose reproduction is sensitive to colour vision (for mate choice), are found to be losing biodiversity at sites with high turbidity resulting from recent eutrophication (Seehausen *et al.* 1997). Detrimental effect of eutrophication to biodiversity is demonstrated vividly in case of Great Barrier Reef on Australia's coast, too. P discharges from intensive coastal agriculture have significantly decreased coral abundance by algal overgrowth as well as promoted the spread of crown of thorns starfish (*Acanthaster planci*), a threat to many coral reefs (Bell & Elmetri, 1995).

In freshwater environments, the most prevalent problems are the blooms of cyanobacteria, which often contain water-soluble neuro- and hepatotoxins (Kotak *et al.* 1993, McComb & Davis, 1993). Additionally, toxic microcystins originating from cyanobacterial blooms have been found from various aquatic organisms including water

snails, mussels, crustaceans and fish, posing so threat to whole trophic network (Gkelis *et al.* 2006).

When it comes to human health implications related to mineral phosphorus fertilizer use, the most apparent of the beneficial effects are higher phosphorus content in foods together with increasing foodstuff supplies. Sufficient P supply is vitally important for humans at all ages, as its deficiency can reduce growth and fertility, as well as damage bone structure. Harmful effects concerning mineral phosphorus fertilizers include foul taste and odour of drinking water as a result of eutrophication. Moreover, in case eutrophicated waters are treated by chlorination, the problem of trihalomethanes arises. Trihalomethanes, disinfectant by-products produced when chlorine reacts with naturally occurring organic matter in surface water supplies, have been reported to have mutagenic and carcinogenic properties (Martin & Cooke, 1994). In addition to that, anatoxin-a together with soluble neuro- and hepatotoxins released by decomposing algal blooms can cause serious health hazards, from neurological disorders and liver dysfunctions to promoting tumour development, being even lethal to livestock and people (Carmichael 1994).

Less well known but potentially rather bothersome is the problem of heavy metals, particularly of cadmium, which is the most enriched element in sedimentary phosphate rocks (Kauwenbergh, 1997). Johnston & Jones (1995, ref. Smil 1999b) report that global average of Cd levels in phosphates is about 21 mg Cd kg⁻¹ of rock, but certain Moroccan rocks have up to 40 mg and phosphates from Togo and Tunisia contain up to 50-55 mg Cd kg⁻¹. Smil (1999b) stresses, that as Florida low Cd-containing phosphates become depleted, the average content of Cd and other potentially hazardous trace elements in the global output of phosphate rock will increase. Cd contamination is reported to result in significant renal dysfunctions in humans, particularly endangered of higher cadmium body burden are women (Cui *et al.* 2005).

Possible solutions to environmental and health effects caused by mineral N and P fertilizers

As the practices up to date regarding to the use of mineral fertilizers in longer perspective are unsustainable, bringing along several detrimental implications to environment as well as to human health, the development and promotion of sustainable solutions are at paramount importance. In case of reactive nitrogen, Galloway *et al.* (2002) propose three specific requirements in order to achieve the abovementioned

goal: *i*) a diminishment in the amount of Nr created by the Haber-Bosch process; *ii*) an increase in the efficiency of reactive nitrogen use in food production (including recycling of agricultural waste); and *iii*) an increase in denitrification of unrecyclable Nr. The first decreases the Nr produced, the second keeps Nr in the agroecosystem, and the third eradicates Nr before it can leak to the environment (Galloway *et al.* 2002). Additionally, the Nr amounts exceeding the agronomic optimum from developed countries could be diminished by directing greater quantities of mineral N fertilizers to developing world that suffers from depletion of soil nutrients.

In developed world, the increased nutrient recycling together with improved Nr use efficiency are the key issues in reducing dependency on mineral N fertilizers. Amplified recycling of plant residues, animal manures, municipal wastes and agro-industrial wastes is expected to complement the N availability and lessen addiction on mineral-N fertilizers (Chambers *et al.* 2000, Tsai 2008). For instance, in case of manure, Roy *et al.* (2002) estimate that if practical problems related to competitive uses and lack of collection would be solved, total of 80 Mt N from manure could replace the 82 Mt fertilizer-N used now.

When it comes to possible solutions related to problems of mineral phosphorus fertilizers use, in general scale, they resemble those related to the Nr. Smil (2000) states the diminishment of phosphorus input and lowering the amount of escaping P as the second best choice after significant reduction in animal food intake of mankind. Some P input reductions, for instance, can be made through more careful fertilization based on soil analyses. Phosphorus applications may even be omitted for some years on phosphorus-rich soils without influencing the yield (Smil 2000). Furthermore, detailed soil analyses and precision farming make it possible to apply P at variable rates within the same field (Wollenhaupt *et al.* 1994, ref. Smil 2000).

Abovementioned practices could somewhat relieve the situation, nevertheless additional measures need to be used. The usage of plant varieties with higher phosphorus uptake efficiency (Egle *et al.* 1999, Römer 2009) and greater recycling of P from urban as well as agricultural waste is at paramount importance (Smil 2000). For instance, in case of Germany, today 48 000 t P from sewage sludge, 12 000 t from animal meal and 9 600 t from meat and bone meal is disposed as waste annually. All this material could, in case of 90% recycling rate, replace over 50% of current mineral P fertilizers (108 000 t P annually) (Römer 2009). Naturally, many of these P recovery methods (for instance, phosphorus recovery as calcium phosphate from sewage sludge)

are still rather expensive. However, the economics of these operations will be much enhanced when P removal becomes mandatory (Smil 2000).

On the other hand, in developing world, the biomass produced on nutrient-poor soils is itself exceedingly poor in essential plant nutrients. Consequently, organic recycling can only solve the essential plant nutrients deficiency to a certain extent. Such soils can be made productive with appropriate amendments and a basic application of plant nutrients (FAO 2006). Some of mineral phosphorus fertilizers that are left unused in developed world as a result of aforementioned methods, could, in case of careful evidence-based planning, contribute to reducing P deficiency in developing world.

Organic fertilizers

Organic fertilizers are soil amendments derived from natural sources that occur either naturally or are processed. The first group encompasses manure, slurry, peat, guano, sewage sludge and green manure, whereas the latter includes compost, fish-, blood- and meat-bone meals, together with wool and seaweed extracts. Additionally, there is great potential of nitrogen-fixing bacteria living freely in soil (James, 2000) that have been used in recent decade to produce commercial fertilizing products that contain deep-frozen bacteria (e.g. Twin N).

Organic fertilizers were a prevailing nutrient source for mankind from the dawn of agriculture; only the last 150 years the man-made mineral nitrogen and phosphorus fertilizers have been replacing these. In case of N, Smil (2002) states, that until 19th century, the mankind had three ways in which to provide it for crops: *i*) recycling of organic wastes (mainly crop residues and animal and human wastes); *ii*) crop rotations including N-fixing leguminous species; *iii*) and planting of leguminous cover crops (vetches, clovers and alfalfas) that were ploughed under as green manures (Smil 2002). In case of phosphorus, the use of soils' natural P levels, accompanied by recycling of locally available organic fertilizers (primarily manure and human excreta, in some areas also guano and apatite) were the traditional methods of meeting plants' demand for P.

As organic matter needs soil living organisms to decompose it to plant-available nutrients, the nutrients release from organic fertilizers generally slower and their positive effect lasts longer than their mineral counterparts. The application of organic fertilizers results in more than just additive nutrient effect; Lowrison (1993, p. 117) states, that enriching the soil with organic materials improves soil structure, leading to improved soil's water and nutrients holding capacity and thereby mitigating risks of

over-fertilization. Additionally, fibrous organic matter (e.g. manure, green manure) can support the aggregation of mineral particles, thereby increasing soil porosity and leading air to the plant bed (Lowrison 1993, p. 117). Bresson (2001) reports that amendment of composted municipal waste decreased aggregate coalescence, resulting in deferred runoff and decrease in soil loss. What is more, delaying crust formation might contribute to reduction of risks of surface water contamination by pesticides or fertilizers (Bresson 2001).

Composts are perhaps the most widespread organic fertilizers globally, Gobat *et al.* (2004, p. 352-355) point out that in addition to improved soil structure, their application changes the chemical properties of soil, as well. Unlike mineral fertilizers, composts add both macro elements and a complement of trace elements highly useful for plants. Additionally, the addition of humigenic substances from compost amplifies the cation exchange capacity, resulting in high inorganic salt content of soils and consequently, promoted root nutrition together with decreased leaching of ions. High inorganic salt content brings along high buffering capacity of composts, thereby compost application stabilizes pH and neutralizes very acid soils. Nevertheless, it has to be taken into consideration, that this effect attains its maximum only several years after application has begun, once the humification process has integrated the materials added through compost (Gobat *et al.* 2004, p. 352-355).

According to Gobat *et al.* (2004, p. 352-355), it is possible to use composting and its products in bioremediation of soils contaminated with pesticides and other xenobiotic compounds as the humic substances bind heavy metals and certain xenobiotic aromatic compounds. Besides, to a great extent, composts contribute to suppression of soil parasites by promoting the activity of antagonistic organisms. The effects that antagonistic microbes pose to phytoparasites are hyperparasitism, competition for bio-elements and energy together with the effect of antibiotic substances secreted by the antagonists (Gobat *et al.* 2004, p. 352-355).

Lairon (2009) states that the food grown organically is at significantly higher quality, expressed by higher content of dry matter, some minerals (Fe, Mg) and antioxidant micronutrients (phenols, resveratrol) than conventionally grown food. While the use of organic fertilizers together with avoidance of agrochemicals are the cornerstones of organic farming, it can be concluded, that the use of organic fertilizers contributes to higher quality of agricultural products, compared to the use of mineral fertilizers (Lairon, 2009).

As the mineral fertilizers' prices rise, the use of organic fertilizers becomes more reasonable in economical terms, as well. For instance, Eltun *et al.* (2002) report the results of an eight-year comparison between six cropping systems (one ecological, one conventional and one integrated farming system, each in forage and arable version) in Norway. Among both arable and forage systems, ecological systems resulted the same or even better compared to conventional, mineral fertilizer use oriented farming systems. Naturally, the good economic results for the ecological farm models depend largely upon higher product prices and government subsidies (Eltun *et al.* 2002), but the poor economics of mineral fertilizer use play a role, as well.

Nevertheless, organic fertilizers do have their drawbacks, too. Disadvantages of organic fertilizers encompass their higher transportation and application costs (due to their dilute concentration of nutrients), variability in their nutrient contents and in case of sewage sludges, potentially toxic heavy metal content. In addition to that, the N/P ratio needs to be paid attention to, as it is commonly lower in organic materials than in plant tissue. Consequently, over-application of phosphorus while fulfilling the N demand could be a threat.

Furthermore, Brady & Weil (2002, p. 505-511) stress the importance of another imperative issue of organic fertilizers- their commonly low nitrogen and high carbon content. The C/N ratio of soils averages generally about 12:1 and high (more than 20) C/N ratio of added organic matter brings along competition for soluble nitrogen between microbes and plants. Consequently severe, even several months lasting, nitrogen deficiency may occur in plants. On the other hand, the application of material with low C/N ratio (less than 20), supplies microbes with more nitrogen than needed, resulting in some of the N from organic compounds to be released into soil solution. Accordingly, the decomposition of added organic matter takes place rapidly, resulting in a period of intense microbial activity together with amplified level of plant-available nitrogen (Brady & Weil 2002, p. 505-511).

Naturally, the C/N ratio varies a lot among different organic fertilizers. Typical high C/N ratio organic materials are straw (up to 80) and sawdust (up to 600), whereas low C/N ratio characterizes composts (about 15), sewage sludges (about 7) and meat and bone meal (about 4) (Brady & Weil 2002, p. 505-511, Jeng *et al.* 2004)

1.2. Meat and Bone Meal

Main characteristics of MBM

Meat and bone meal (MBM) is a by-product of the slaughtering industry that is today increasingly used as an organic fertilizer. The process of converting waste animal tissue into stable, value-added materials like MBM is called rendering. The methods and raw materials of MBM production differ to some extent, but the general production principle is that animal leftovers are minced, sterilized, fat is separated and ultimately the protein-rich mass is milled into fine meal.

Meat and bone meal consists of about 50 % protein, 35 % ash, 8-12 % fat and 4-7 % moisture; its plant nutrient content approximates to 8 % N, 6% P and 0.5 % K. Additionally, MBM contains 11-15 % Ca, 0.19-0.25 % Mg and 0.2-0.4 % S, together with mineral substances from which the most significant are Se (0.28 mg/kg dry matter) and B (0.25-0.27 mg/kg dry matter). The average organic matter content is 50 %. Nevertheless, as the raw material of MBM varies largely, so does the nutrient content of it.

Production and use of MBM

According to various authors (for example, Simonen, 1948, p. 279-280 and Lowrison 1993, p. 226-227), the historic use of animal residues as fertilizers dates back for thousands of years. For instance, bone meal was used as a fertilizer for fruits in Mediterranean region already in Roman times. Simonen (1948, p. 279-280) states, that significant amounts of bone meal were used as fertilizer in England starting from late 18th century. The Britons' demand for that valuable phosphorus fertilizer is reported to have been enormous- more than 100 000 tons of bones of all origin were imported annually from all over Europe as well as from South-America. At first, the fertilizing effect was rather slow as untreated bones were just milled before used on fields. Later the extraction of fat and proteins from the raw bone material improved the fertilizing effect of bone meal (Simonen 1948, p. 279-280).

The industrialization and development of steam technology in 18th-19th century caused the rapid growth of the rendering industry, resulting in greater amounts of its products: grease, tallow and protein meals (MBM among them). In pursuit of higher effectiveness, a batch dry rendering process was invented in the 1920s, resulting in higher efficiency in energy use and a better protein yield compared to traditional wet

process. By the end of World War II, most rendering facilities were using the dry process, which initiated the proliferation in using meat and bone meal as a protein feed for agricultural animals and raw material of pet food. Due to the higher profitability of MBM as a protein feed, the fertilizer use was nominal.

The situation changed dramatically in 1994 as the EU banned the use of MBM as a feed for ruminants and, consequently, in 2001, as a feed for all livestock (Ylivaino *et al.* 2008). The reason for that was the outbreak of bovine spongiform encephalopathy (BSE), commonly known as ‘‘mad cow disease’’. Furthermore, EC Regulation No. 1774/2002 of the European Parliament and the Council additionally restricted the use of MBM as a fertilizer in 2002. Subsequently, MBM was used as landfill, incinerated or used as an alternative fuel in cement production. Nonetheless, in the spring of 2006, restrictions on MBM usage as a fertilizer were lifted in all regions of the EU (The Commission of the European Communities 2006, Ylivaino *et al.* 2008).

By 2005 the distribution of animal meals and processed animal proteins (PAP) in EU 17 was following: 52% were incinerated, 23% were used as pet food and 20% as fertilizers (Coelenbier 2006). By 2008, the distribution had somewhat changed: the share of energy production (incineration) contributed only 39%, having lost its share to pet food (33%) and fertilizers (24%) (Nielsen, 2009). The differences could partially be also due to the fact that in 2008, the comparison was made within EU 20 instead of EU 17

When it comes to modern production methods of meat and bone meal, some variation between different facilities exist, but according to Nielsen (2003), some of the main processes are following: 1) by-products from slaughterhouses (bones, heads, skins, intestines etc.) are transported to the factories in closed containers, 2) the products are minced, 3) the minced meat is coagulated by heating (80-90°C), 4) solid and liquid material is separated by pressing, 5a) the solid fraction is dried (110°C), 6a) the dry product is screened, sterilised (133°C), packed and stored for distribution, 5b) the wet fraction is heated (105°C) and fat is separated, 6b) fat is sterilised (125°C), packed and stored for distribution. The wastewater generated during the process is either treated completely and emitted to recipient or treated to some extent and directed to further treatment in municipal wastewater treatment plants. Ventilation air is treated in bio-filters (Nielsen 2003).

Production and use in Finland

From year 2000, animal waste was classified in Finland according to Decisions of Ministry of Agriculture of Finland (1022/ VFD/2000) as follows: “low-risk material” if it did not present a serious risk or “high-risk material” if it was suspected of presenting serious health risks to humans or animals; the latter included animals which died on the farm, stillborn and unborn animals, and spoiled and condemned materials (Salminen 2002). Additionally, the Decision of Ministry of Agriculture (1197/VFD/2000) identified the requirements for the disposal and processing of “specified risk material (SRM)” including certain materials from cattle, sheep and goats, (e.g. brain tissue and spinal cord) or, which had been found to carry a risk of transmitting the BSE (Salminen 2002). Differently from “low-risk material” and “high-risk material”, SRM could not be used as feed or fertilizer, it needed to be incinerated or buried into ground.

Salminen (2002) reports, that in 2000, Finland produced altogether about 200 000 tons of animal by-products (Fig. 1.3.), majority of it (about 170 000 tons), low-risk material, including slaughterhouse waste and waste from fur animal production. Other two categories both contributed about 15 000 tons, including dead farm animals and slaughterhouse waste. When it comes to recovery of animal by-products, most of it was produced into fur animal feed in feed production plants, leaving about 60 000 tons for recovery in rendering plants (Salminen 2002).

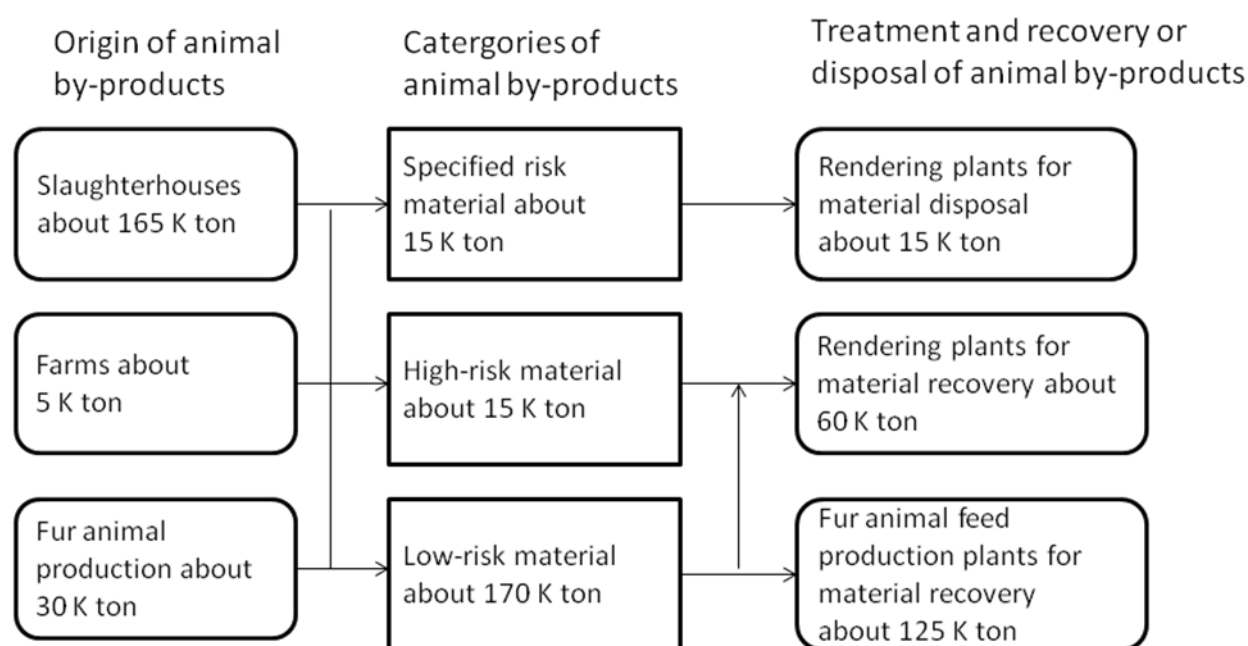


Figure 1.3. The amount and the disposal and the recovery of animal by-products in Finland in 2000 (Salminen 2002).

The classification of animal by-products changed in all EU countries, including Finland, in October 2002, with the ratification of the regulation No 1774/2002 of the European Parliament and of the Council. From then on, Category 1 material includes all body parts of animals suspected in being infected with Transmissible Spongiform Encephalopathies (TSE) and specified risk materials. Category 2 contains animals that die other than being slaughtered for human consumption or products of animal origin containing residues of certain veterinary drugs and contaminants. Category 3 includes parts of slaughtered animals, which are unfit for human consumption (but are not affected by any signs of diseases communicable to humans or animals) and skins, hooves and horns, pig bristles and feathers originating from animals that are slaughtered in a slaughterhouse (The European Parliament and the Council 2002). Since spring 2006, last two categories are allowed to be used to produce organic fertilizers (The Commission of the European Communities 2006).

In the present day, there are two rendering facilities producing MBM in Finland, (Honkanjoki OY and its sub-company Findest Protein OY). Those two companies produced in 2007 approximately 21 000 tons of meat and bone meal, main uses of which were fertilizer and fur animal feed (Valkosalo 2008). In 2007, 3500 tons of MBM were used as fertilizers in Finland (Kivelä 2008).

MBM as a nitrogen fertilizer

Despite the facts that nitrogen compounds contribute only 8% of the MBM and that mineral N contribute only minor portion of total nitrogen, the low C/N ratio of MBM (about 4) provides great potential for N mineralization (Jeng *et al.* 2004). The potential of MBM as an effective organic fertilizer was supported by the large increase in available N and the enhancement of the biomass and activity of soil microorganisms in an incubation experiment (Mondini *et al.* 2008). Soil amendment with MBM caused a remarkable increase in both extractable NH_4 and NO_3 (about 50% of added N), together with enhanced microbial content and activity in soil. Furthermore, microbial biomass increased as a function of the rate of MBM application and the addition of readily available C did not cause limitation in other essential nutritive elements, as was shown by respiration dynamics (Mondini *et al.* 2008).

The effects of MBM as N fertilizer were evaluated by Salomonsson *et al.* (1994, 1995). In case of spring wheat, Salomonsson *et al.* (1994) found no significant

difference in grain yields between MBM and urea; both resulted significantly better than slurry manure. MBM gave better increase in protein content of the yield than manure or urea when the N application was split. Thereby it was recommended to divide the MBM treatment and in addition to half the fertilizers applied at sowing, give a supplemental rate at Growth Stage (GS) 30-31 to increase the grain protein content. It was additionally advised, that in order to obtain the same level in protein content and yield, the rate of N can be lower in case of MBM than for slurry manure. In case of winter wheat, Salomonsson *et al.* (1995) report that the protein contents of grain fertilized with MBM was as good as when urea was used.

Moreover, there have been several field trials conducted with cereals in Finland in order to find out the fertilizing effect of MBM-N compared to mineral fertilizers. In case of barley and oats, MBM resulted in as high grain yields as did mineral fertilizer (Kemira's Y3® 20N-3P-9K) (Chen L., 2008). Additionally, Kivelä (2007) reports the fertilizing effect of MBM being 96% of the Kemira's Y3® chemical fertilizer in case of oats during a three- year field experiment in Finland. Furthermore, a 24% higher residual effect was present in case of MBM, compared to mineral Y3 fertilizer (Kivelä, 2007).

Jeng *et al.* (2004) found that increasing amounts of MBM gave significantly improved yields, even though mineral N fertilizer resulted in significantly higher barley yield than MBM in case of pot experiment. That could have been partially due to N immobilisation because of relatively high C/N ratio of growing substance (sand/peat mixture). That reasoning is supported also by the fact that in the following, spring wheat experiment on field (C/N ratio of the soil 9), there was no period of N immobilisation and good N effect was found also for small amounts of MBM (total N 50 kg ha⁻¹). At higher N levels (total N 100 kg ha⁻¹) in field experiment, MBM yielded as good as mineral N fertilizer. In general, if MBM is applied to cereals in spring, the relative N efficiency of MBM compared to mineral fertilizer is at least 80% or higher (Jeng *et al.* 2004). Additionally, Jeng *et al.* (2006) suggest that the effect of MBM is greatest on soils with low content of soil organic matter (SOM) and limited supply of N mineralized from SOM.

When it comes to nitrogen uptake efficiency (NUE), Equation 1 is commonly used:

$$\text{NUE (\%)} = 100(\text{Xf} - \text{X0})/\text{Xr} , \quad (1.)$$

Xf = N yield (kg ha⁻¹) from fertilized plots

X0 = N yield (kg ha⁻¹) form unfertilized plots

Xr = N application rate (kg ha⁻¹).

Jeng *et al.* (2004) found in the field experiment equal or slightly lower NUE of MBM (25-42%) than mineral N fertilizer (43%). In pot experiment, MBM had only half the NUE of mineral N fertilizer (possibly partly due to abovementioned N immobilisation problem in greenhouse). In experiments conducted with wheat, no significant differences in nitrogen uptake efficiency were detected between MBM and urea, in most cases they both resulted significantly better than slurry manure (Salomonsson *et al.* 1994, 1995).

The baking performance of crop is important for deciding about the quality of it. The white flour composition, dough properties and baking performance of spring and winter wheat treated with MBM, slurry manure and urea did not differ significantly between fertilizers (Fredriksson *et al.* 1997, 1998). Nevertheless, higher N application rates notably increased flour protein content and dough development time but decreased dough softening (Fredriksson *et al.* 1997, 1998). Additionally, Salomonsson *et al.* (1995) report that in case of MBM fertilization, there were no quality concerns of the grain yield with the problems of moulds, colony-forming fungi or endogenous infections and no differences between treatments (MBM, urea and manure slurry) were detected. Also the grain contents of Pb and Cd were lower than the limits given by the Swedish National Food Administration and recommendations from the food industry (Salomonsson *et al.* 1995).

An issue of paramount importance is the environmental effect of MBM. Jeng & Vagstad (2009) conducted laboratory experiment, where nitrogen and phosphorus leaching effect of MBM could be estimated. MBM fertilization on different N levels (60, 120 and 180 kg ha⁻¹) together with mineral fertilizer were applied to soil columns (without crop cover) and leached nutrient contents analyzed. The nutrient leaching from MBM-treated columns turned out to be approximately three times lower than those treated with mineral N fertilizer, NO₃-N leaching losses being only 13-17% of applied N, compared to 31% of mineral fertilizer. It needs to be taken into consideration, that the nutrient losses observed can be expected to be significantly lower in the presence of a vegetation cover. Anyhow, bearing in mind that leaching losses tended to increase together with increasing MBM application rate and that N-mineralization takes place relatively rapidly, the suggestions were made that early spring or late autumn application should be avoided. Additionally, the high P content of MBM prevents fulfilling the whole N demand of plants by using MBM (Jeng & Vagstad 2009).

MBM as a phosphorus fertilizer

Taking into consideration that the sources for mineral P fertilizers (to a great extent, phosphate rock) are limited, the necessity of increasing the return rate of large P resources from animal by-products to the agricultural nutrient cycle is obvious (Smil, 2000, Werner 2003, Kivelä, 2007). The phosphorus content of MBM varies from 5 to 9%, being mostly influenced by the bone content of raw material. Most of the MBM-P is present as calcium phosphate ($\text{Ca}_5(\text{PO}_4)_3\text{OH}$) in the bone fraction and in organic form in the meat fraction. However, due to its chemical nature, the P in MBM is classified as being scarcely soluble (readily plant available (P-AL) content 19-40%) (Jeng *et al.* 2004, 2006, Ylivainio *et al.* 2008, Ylivainio & Turtola, 2009)

According to Jeng *et al.* (2006), the efficiency of added P depends mostly on the quantity of residual P in soils. Application of MBM as a phosphate fertilizer brings along significant increase in the labile pool of available P and consequently, the capacity of soils to adsorb additional phosphate can be expected to decrease (Jeng *et al.* 2006). In case of leek seedlings inoculated with arbuscular mycorrhiza, Kahiluoto and Vestberg (1998) reported a significantly larger P uptake from bone meal than from Kola apatite. Bone meal (P content 7.4%) increased the acetate-extractable P contents of soil significantly, whereas Kola apatite had no influence on soil acetate-extractable P contents. The inoculation of seedlings with arbuscular mycorrhiza increased P uptake only on conventionally managed soil monocropped with cereal, the effect was even negative on organically cultivated soil. From that it can be concluded, that under certain conditions, MBM-P uptake can be greatly amplified on the presence of arbuscular mycorrhiza in soil (Kahiluoto and Vestberg 1998).

Jeng *et al.* (2006) conducted a greenhouse experiment, where fertilizing effects of MBM and mineral NPK fertilizer were compared in case of barley and ryegrass. They concluded that in case of equal N supply, barley and ryegrass yields did not differ significantly between the NPK and MBM treatments. As the relative P efficiency of MBM-P was about 50% compared to phosphate-P in the first crop, MBM can be considered as a rather effective P fertilizer. Additionally, in case of field trials, it was found that the P in MBM had residual effect the year after application. On plots, where at least 500 kg MBM ha⁻¹ was applied there was no need for additional P. Anyhow, it should be kept in mind, that the N/P ratio of MBM is considerably narrower than the normal nutrient uptake ratio of cereals, resulting in P accumulation in soils on levels of environmental concern in case of annual application of MBM. It is therefore

recommended that if MBM is used to meet the N fertilizer demand of the crops, P application the following year should be omitted (Jeng *et al.* 2006).

Ylivaino *et al.* (2008) compared the P availability of MBM, superphosphate (SP), and cow manure in a 3-year pot experiment with ryegrass. MBM-P immediately available to plants contributed only 19 % of the availability of P from SP and dairy manure, however for the 3-year period with ten ryegrass cuts, the P availability of MBM increased to 63 %. Another important factor influencing P release from meat and bone meal is pH. Bone meal may be a more effective P fertilizer in acid soils than in soils with pH>6. Generally, as MBM showed the strongest effect in increasing the acid-soluble P concentrations in the experimental soil, its use as a long-term P supply for perennial plants in non-calcareous soils is encouraged by Ylivaino *et al.* (2008). The field trials following the greenhouse experiment supported the conclusion of longer effect of MBM-P, especially in case of perennial plants. Even though the phosphorus availability of MBM was merely 18 % of the P availability of SP-P during the year of application, the P of MBM was equal to SP in following years. Altogether, the availability of MBM-P in 3-4 experimental years reached 32 % of SP-P. Furthermore, the highest availability of MBM-P (up to 100% of SP-P) was found in case of grassland 3-4 years after application (Ylivainio & Turtola, 2009).

When it comes to environmental effects of MBM-P, the P leaching is reported to be minor even from soils without vegetation cover (Jeng & Vagstadt 2009). The annual rates of orthophosphate (PO₄-P) losses were small for all treatments, rarely exceeding 0.3 kg ha⁻¹ or 0.5% of the total P applied. Naturally, the losses may be expected to increase considerably when MBM is applied as N fertilizer. The highest application rate of MBM (2280 kg ha⁻¹ or 180 kg N ha⁻¹) showed significantly higher PO₄-P losses relative to the other treatments (Jeng & Vagstadt 2009).

1.3. Industrial Ecology

Development of the concept

Industrial ecology (IE) is the discipline that, using life-cycle analysis, traces the flow of energy and materials from their natural resources through industry, the use of products, and their final recycling or disposal. Industrial ecologists aim to minimize energy use, pollution and waste in industrial systems by creating industries in which every waste is a raw material for another product (Encyclopædia Britannica, 2009). Graedel & Allenby (2003, p. 18) stress, that the concept of IE requires an industrial system to be viewed in

unison with its surrounding systems, not in isolation from them. It can be concluded, that an ecological industrial system should function as a particular case of an ecosystem - but based on infrastructural capital rather than on natural capital.

Industrial ecology as a discipline is rather young- the starting point of it is recognized to be the article “Strategies for manufacturing” written by Frosch & Gallopoulos (1989). They used samples of PVC, iron and platinum-group metal industries to bring out the idea of an industrial ecosystem. Such a system would function as an analogue of biological ecosystem, in which the consumption of energy and materials is optimized and the effluents of one process serve as the raw material for another process, resulting in minimal waste generation. Although they conclude that an ideal industrial ecosystem may never be attained in practice, they find it crucial to both manufacturers and consumers to change their habits to approach it, as it seems the best alternative for coping with environmental issues arising from the population growth (Frosch & Gallopoulos, 1989).

As biological ecosystems can be extended to include the interactions of industrial ecosystems, Graedel (1996) illustrated the idea of IE by depicting material cycles in case of three biological concepts. Firstly, he described an open primitive biological system such as could have existed early in Earth’s history (Fig. 1.4a). With almost unlimited amount of usable resources and relatively small amount of living organism, there was no practical need for recycling, so resource flows within the system were minor compared to the flows into and out of the system.

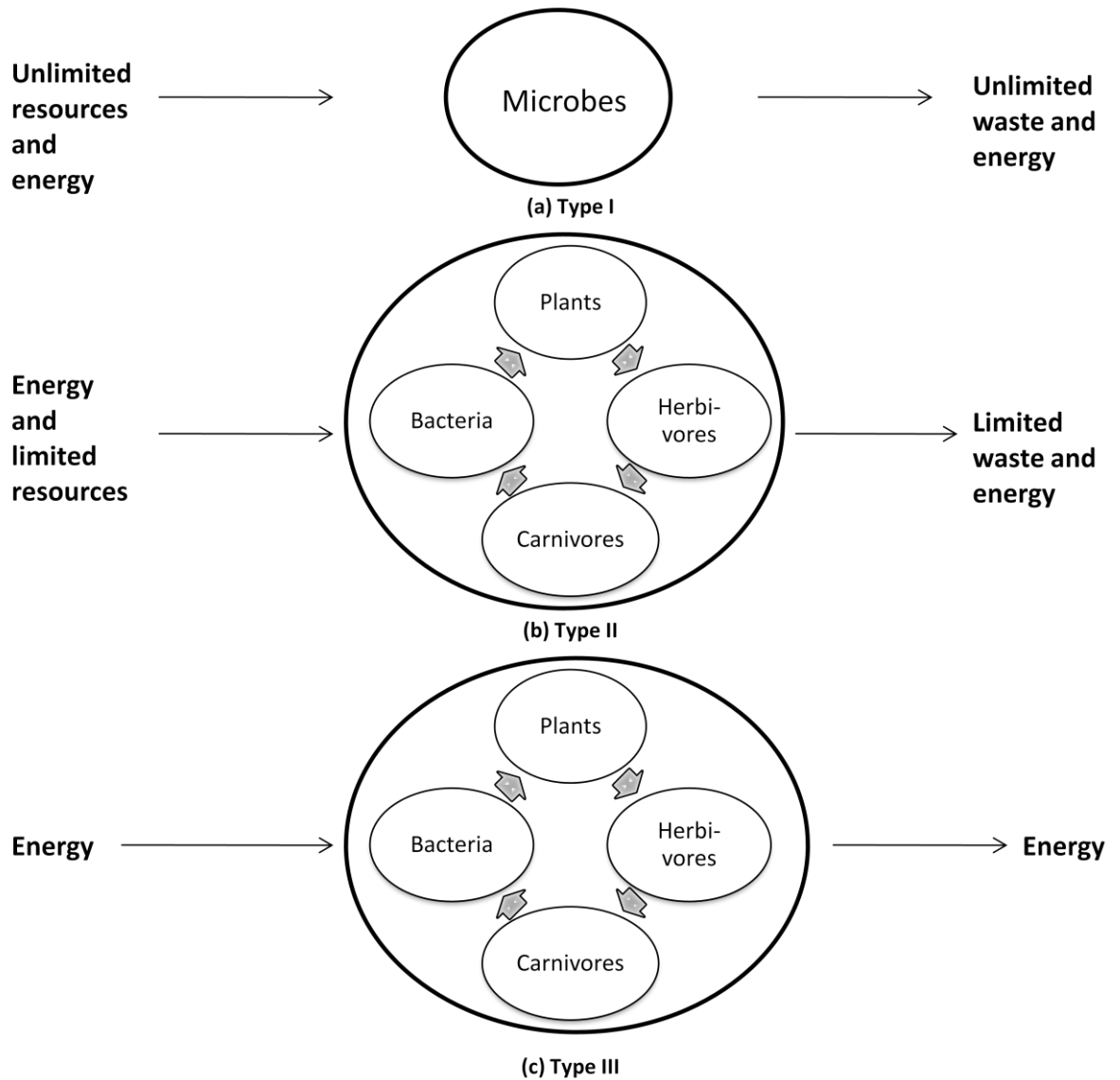


Figure 1.4. (a) Linear materials flow in open Type I biological ecology. (b) Quasi-cyclic material flows in closed Type II biological ecology. (c) Cyclic material flows in Type III biological ecology (Graedel, 1996, revised).

As the early life forms multiplied and resources grew limited, Type I systems evolved to Type II closed biological systems (Fig. 1.4b), leading to resource cycling instead of linear material flow. In Type II systems, the flows of material within the system are larger than the flows into and out of it.

Although the efficiency of Type II system is much higher than a Type I system, on a global scale, it is unsustainable over the long term as the flows are all still in one direction; causing the system to “run down.” In order to be ultimately sustainable, the global biological ecosystem has evolved to completely cyclical Type III system (Fig. 1.4c) where waste to one component of the system represents resources to another.

When it comes to industrial ecosystems, the ideal anthropogenic use of the materials and resources available would be mimicking the cyclic biological model (Fig. 1.4c). Conversely, the resource use of mankind has historically been characteristic to Type I system, resulting in remarkable economic and environmental costs. The implementation of industrial ecology is anticipated to achieve the evolution of technological systems from Type I to Type II and perhaps even to Type III, by optimizing holistically all the factors involved (Graedel 1996, Graedel & Allenby, 2003, p. 49-53).

Korhonen (2001) elaborated the idea of IE by suggesting that the perfect industrial ecosystem consists of an industrial subsystem surrounded by the natural ecosystem, both functioning according to the same principles of system development: recycling, diversity, locality and gradual change. The core idea of this concept is that the industrial subsystem can be sustainable only if it strives towards greater diversity in cooperation between the actors involved (i.e. farmers, waste treatment companies and consumers) for recycling each other's waste materials and energy. Additionally, the usage of imported resources and transportation should be minimized; instead, a sustainable industrial subsystem needs to develop gradually following the renewal rate of the local renewable resources. Ideally, the Type II system for the industrial subsystem would be achieved (with only renewable resources as input and residues recyclable for the nature as output) and Type III system for the system as a whole (with solar energy being the only input and waste heat the only output). Such an approach would result in both environmental and economic gains as the raw material inputs as well as waste outputs are reduced (Korhonen 2001).

Moreover, the application of industrial ecosystem is reported to bring along social gains, as well. For instance, Niutanen & Korhonen (2003) advocate the shift of agriculture from conventional, linear material flow system to Type II system by suggesting economic, ecological and social wins. The social gains are represented by additional employment opportunities through local utilisation and management of the material and energy flows as well as increased cooperation between local institutions (Niutanen & Korhonen 2003).

The importance of expanding the focus of industrial ecology from ecological and economical viewpoints to the social dimension of sustainable development was additionally stressed by Von Hauff & Wilderer (2008). They advocated the use of "Integrated Sustainability Triangle" (Fig. 1.5., originally introduced by von Hauff & Kleine (2005)) as an implementation method for the systemization and evaluation of the

performance of companies regarding sustainability management. Usage of “Integrated Sustainability Triangle” can assist developing sustainable strategies for institutions based on three dimensions of sustainable development – ecology, economy, and society (Von Hauff & Wilderer 2008).

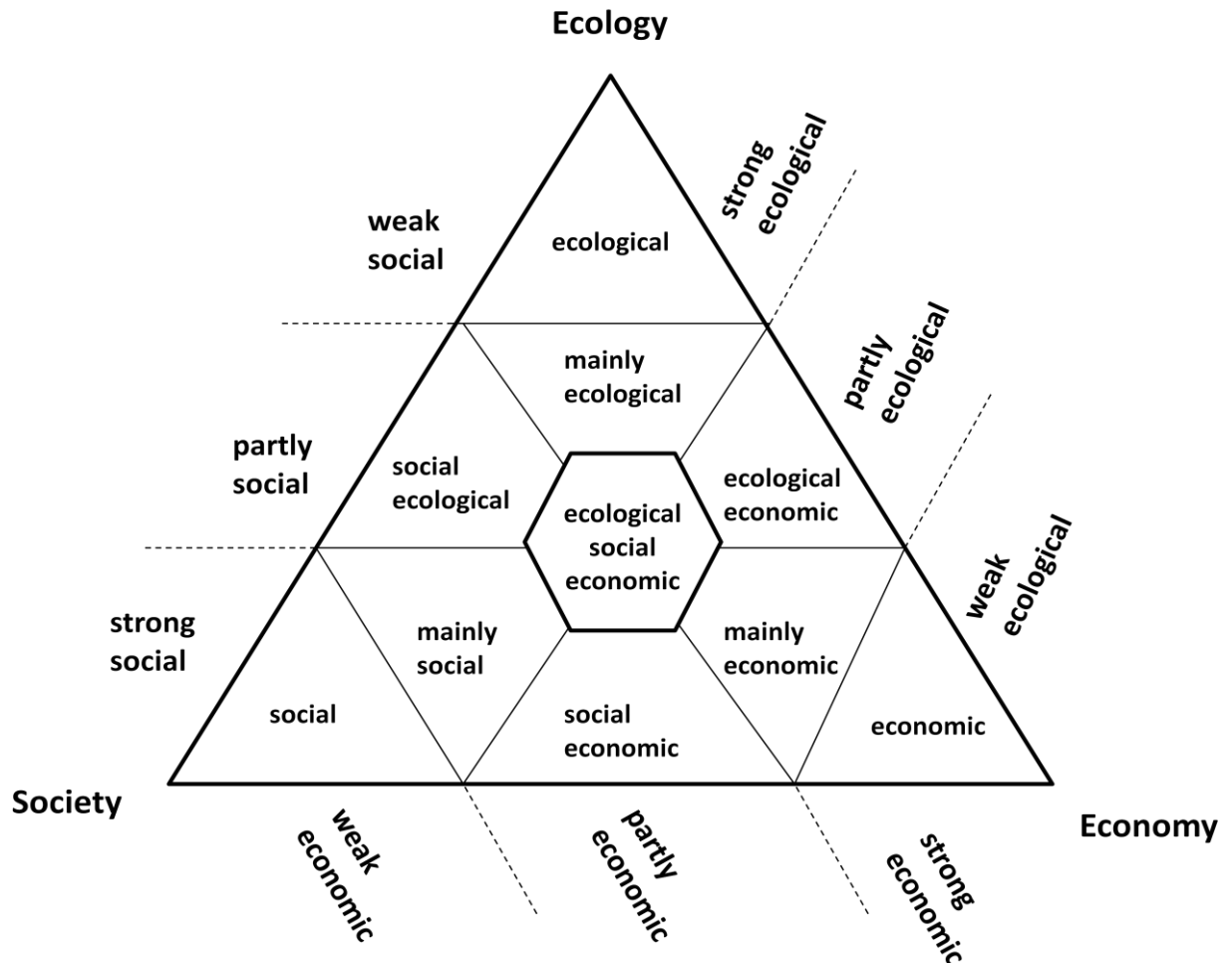


Figure 1.5. Integrated Sustainability Triangle, subdivided into fields of ecological, social and economic significance (adapted from Von Hauff & Wilderer 2008).

Application of industrial ecology in agriculture

The extreme dependency on natural ecosystem makes agriculture a perfect field for applying the principles of industrial ecology. The resource use of agriculture has traditionally been characteristic to cyclical ecosystems. Regrettably, in the era of industrialization, the Type I system has extensively been mimicked, resulting in remarkable economic, environmental and social costs. The application of the principles of industrial ecology could support the evolution of agricultural systems from linear material flow to Type II and perhaps even to Type III cyclical systems, by optimizing

holistically all the factors involved, as suggested by Graedel and Allenby (2003, p. 49-53) (Figure 1.6.).

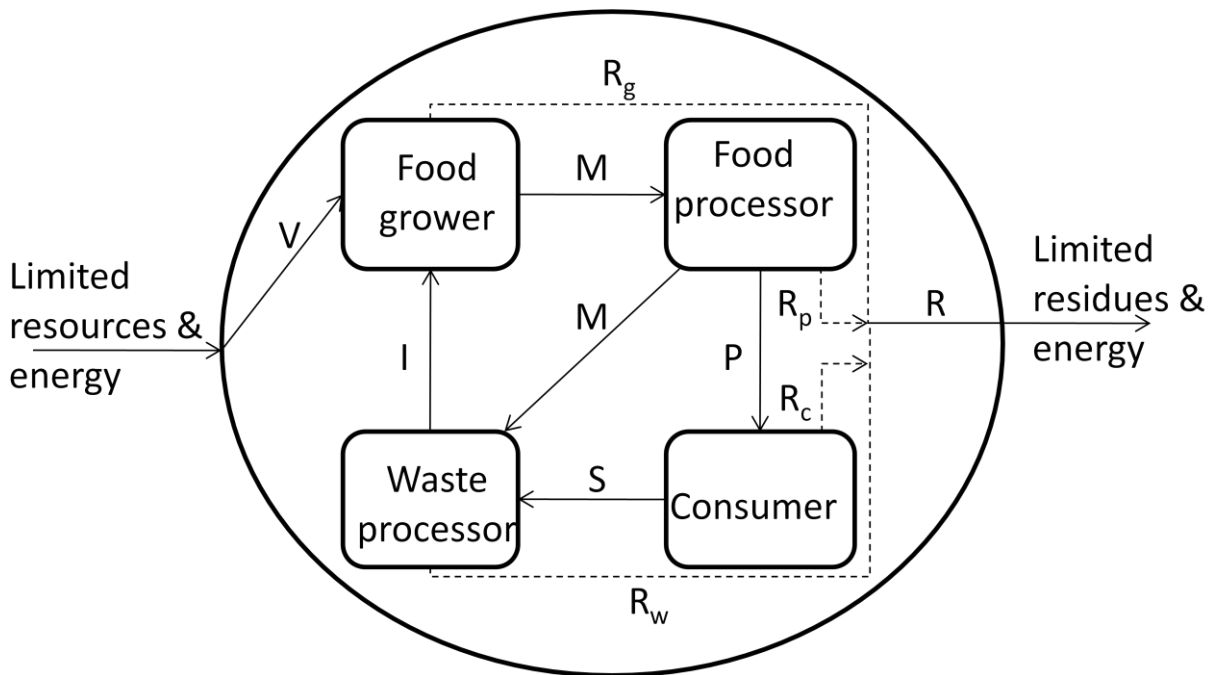


Figure 1.6. The Type II materials flow model of IE in case of agriculture. The letters refer to the following mass flows: V = virgin material (i.e. fertilizer); M = raw agricultural product; P = product; S = salvaged residues; I = recycled, ready-to-reuse nutrients; R = uncaptured residues; g = grower; p = processor; c = consumer; w = waste processor (Graedel & Allenby, 2003, p. 53, revised).

The “Closed Substance Cycle and Waste Management Act” that came into force in 1994 in Germany is an excellent example of growing worldwide consciousness of the finiteness of certain natural resources, like sources for mineral fertilizers (phosphorus rock and fossil energy) (Werner 2003). Consequently, the necessity for increased recycling of nutrient containing communal and industrial wastes in agriculture has globally become an essential priority.

The efficiency of applying a roundput method (anaerobic digestion and later fertilizer-use of biowaste and sludge from wastewater treatment) to agriculture and food sector of Finland was analyzed by Niutanen & Korhonen (2003). They concluded that the roundput method resulted significantly better than the conventional throughput (linear material flow) methods, both environmentally (fewer greenhouse gases emissions and nutrient losses) and economically (higher cost-efficiency if emission costs taken into account). Furthermore, the application of industrial ecology is reported to result also in social win, as the employment opportunities are predicted to be on rise in the sector of renewable technologies (mainly in building and maintaining facilities

like biogas reactors and pumps) (Niutanen & Korhonen 2003). The higher social sustainability of more labour-intensive Type II system agriculture compared to conventional agriculture that relies on mineral fertilizer use is advocated by Mancus (2007), as well.

As the recycling of nutrient- rich industrial waste is considered as an effective way of replacing mineral fertilizers and thereby approaching the Type II system in agriculture, the fertilizer use of meat and bone meal should also be increasingly paid attention to.

The use of non-renewable phosphorus rock for fertilizer production is a classic example of linear material flow model. The same applies to the production of mineral nitrogen fertilizers- a process consuming an estimated amount of 2-3% of global annual energy supply (primarily derived from non-renewable sources-natural gas or oil) (FAO 2006, EFMA 2008). Additionally, the output of a system using mineral N fertilizers mimics the Type I system- harmful gaseous nitric compounds are emitted to environment during the production process and also the nitrate leaching from soils to environment is reportedly higher than in case of meat and bone meal (Galloway and Gowling 2002, Jeng & Vagstadt 2009). Therefore, it can be concluded, that the increased fertilizer use of recycled nutrients from MBM is clearly an important step towards sustainable agriculture that follows the principles of industrial ecology.

1.4. Objectives of the Study

Various authors have previously studied the fertilizer use of MBM (Salomonsson *et al.* 1994, 1995, Jeng *et al.* 2004, 2006, Kivelä 2007, Chen L. 2008, Mondini *et al.* 2008, Ylivainio *et al.* 2008, Jeng & Vagstadt 2009, Ylivainio & Turtola 2009). Attention has been paid to a variety of characteristics including yield effects to various crops, nutrient use efficiencies, effect to the soil microorganisms and also the nutrient leaching rate from soils fertilized with MBM. Nevertheless, there seems to be need for additional research of the effects of MBM as a grassland fertilizer, especially the nutrient use efficiencies and uptake patterns together with post-harvesting soil quality.

In addition to the yield effect, the duration of the fertilizing effect is essential, as well. The duration of the fertilizing effect is usually dependant on the content of readily plant-available nutrients of the fertilizer as well as on their mineralization rate. As the nutrients of MBM are mostly in organic form, and need to be mineralized to become

usable for plants, it can be presumed that the yield effect of MBM lasts longer than mineral fertilizers.

Although the low K content of the MBM is widely recognized, there still is lack of research on the issue, how MBM effects in mixture with fertilizers with high potassium content. Such a mixture could justify using MBM on fields, where potassium is limiting nutrient.

Nutrient use efficiency of fertilizers is a characteristic of utmost importance for farmers, as it demonstrates the efficiency of applied mass unit of fertilizer, whereas post-harvesting quality of soil provides information about the possible residual effect of fertilizers. For instance, MBM is reported to have significant residual effect of phosphorus for following years. Differently from majority of mineral fertilizers, the P application can even be omitted in case of at least 500 kg MBM ha⁻¹ (Jeng *et al.* 2006).

Consequently, the aim of the experiment is to provide answers for following questions:

1. What is the yield effect of MBM to ryegrass compared to mineral fertilizers? Is the fertilizing effect of MBM longer than that of mineral fertilizers?
2. Which would be the yield effect of a mixture of MBM and a high potassium content fertilizer?
3. How effectively are the nutrients of MBM (N and P) used by ryegrass, compared to mineral fertilizers?
4. How does MBM affect the post-harvesting soil quality, compared to mineral fertilizers?

2. Materials and methods

2.1. Materials used in experiment

Italian ryegrass

Italian ryegrass (*Lolium multiflorum*) is a non-leguminous forage grass cultivated around the world. The species commonly needs relatively high soil fertility, in case of which it yields fairly high. The tetraploid cultivar used in this experiment, Meroa, has an average dry matter yield in Finland of 8000-9000 kg ha⁻¹ (Kangas *et al.* 2003).

Five fertilizers used in the experiment

There were five different fertilizers used (Table 2.1.), in addition to reference treatments (control and PK treatments). PK refers to a granulated garden fertilizer by *Kemira GrowHow Oy*, Puutarhan PK®, which is produced for fall fertilizing of garden plants. It was used in the experiment in order to get a comparative fertilizer with high potassium and minimal nitrogen content.

Meat and Bone Meal (MBM) is a meal type fertilizer originating from Honkanjoki OY. In addition to NPK contents, it contains also 11-15% Ca as well as minor amounts of Mg and S (0.19-0.25% and 0.2-0.5%, respectively).

The second fertilizer, MBM mixture (MBML), is a granulated mixture of 97% MBM and 3% potato cell liquid originating from starch industry. Such a mixture results in somewhat higher potassium content than regular MBM does.

Next, a mixture of MBM (71.4%) and mineral fertilizer PK (28.6%) (MBMPK) was added to experiment in order to study the effect of mixing MBM with K fertilizers.

The Y4PK stands for a mixture of Pellon Y4® (62.5%) and PK (37.5%). Pellon Y4® is a granular mineral fertilizer produced by *Kemira GrowHow Oy*. In addition to relatively high potassium content, it contains remarkable amounts of sulphur (NPKS 20-

2-12-2). Such a mixture was made in order to achieve the theoretical uptake ratio of phosphorus and potassium of plants.

Finally, Nurmen NK® (NK) is a granulated mineral product of *Kemira GrowHow Oy*; it was used in order to show the effect of nitrogen and potassium fertilizer when there was no phosphorus added.

Table 2.1. Fertilizers used in the experiment, and their nitrogen, phosphorus and potassium contents.

Fertilizer	Abbreviation	N%	P%	K%
Meat and Bone Meal	MBM	8	6	0,5
MBM+ potato liquid	MBML	8	5	1
MBM + Puutarhan PK®	MBMPK	6.5	5.5	5.5
Pellon Y4 (+PK)	Y4PK	13.5	3	14.5
Nurmen NK®	NK	20	0	14

Soil used in experiment

The soil used in the greenhouse experiment originated from a field that was used for decades as an organic field, mostly as a leguminous pasture and barley. Prior to starting the experiment, soil analyses were carried out by Viljavuuspalvelu OY, their methods meet the standards of EN ISO/IEC 17025 accreditation. The soil type was finesandy till and it contained approximately 3-5.9 % of organic matter (Table 2.2.).

Table 2.2. Results of soil analyses by Viljavuuspalvelu OY prior to starting the experiment.

Factor	Result	Estimation
pH	5.9	Slightly acid
Ca	1500 mg l ⁻¹	Satisfactory
P	18 mg l ⁻¹	Good
K	190 mg l ⁻¹	Satisfactory
Mg	150 mg l ⁻¹	Satisfactory
S	12 mg l ⁻¹	Satisfactory
Cu	4.1 mg l ⁻¹	Satisfactory
Mn	22 mg l ⁻¹	Unsatisfactory
Zn	4.59 mg l ⁻¹	Satisfactory

2.2. Growing conditions

Five litre classical experimental pots were used throughout the experiment, the sowing date was July 20 2007 and the final yield was removed February 12 2008. From sowing to the third cut removal, October 23 2007, the plants were grown in a curtain-walled, but roofed special pot experiment hall. Nevertheless, the temperature and solar radiation for this period were uncontrolled (Table 2.3.).

Table 2.3. The mean temperature and solar radiation from July to October 2007 according to Viikki meteorological station.

Month	Mean temperature, °C	Mean solar radiation, W m ⁻²
July	17.22	198.94
August	17.47	187.73
September	11.35	98.49
October	6.86	42.52

However, after third cut, pots were brought in to the greenhouse where light and temperature were controlled. The day/night temperatures were recorded throughout the growing period and they were set to 21 and 16 °C respectively, after reaching these limits, the roof windows opened automatically. Natural light was supplemented with a set of regular fluorescent lamps (the irradiance being approximately 200 W m⁻²), adjusted above the plants to a 16/8 h light/dark period.

2.3. Experimental design

The experiment was arranged to include a factorial design with fertilization (“Fertilizer”) and nitrogen level (“Nitrogen”) as the two factors. There were five levels for the Fertilizer (see Table 2.1): MBM, MBML, MBMPK, Y4PK and NK. The levels for Nitrogen were set to equal 80, 160 and 240 kg N ha⁻¹. The factorial design, hence, included 5 x 3 = 15 treatments, as combinations of the levels of the two factors.

In addition, the experiment included four additional reference treatments. These were the control without fertilization (Control), and three levels of PK (PK I, PK II and

PK III). The PK reference treatments were used in the experiment in order to get comparative fertilizers high in phosphorus and potassium content, at the same time having minimal nitrogen content.

The experiment was arranged as a completely randomized layout with four replications for each treatment. It was a pot experiment in the greenhouse of the Department of Agricultural Sciences, University of Helsinki Viikki campus. Five-litre cylindrical pots of 314 cm² soil surface area were used. The soil was mixed, sieved and transported to greenhouse, where it was measured to the pots, 3.5 kg of soil to each pot. The pots were located side by side on a greenhouse table. The outermost rows were of pots not involved in the experiment in order to avoid edge-effects.

Contents of the major nutrients (N, P and K) in each treatment are given in table (Table 2.4). In order to get calculated nitrogen levels for field to correspond to pot experiment, N levels were calculated to 229, 457 and 686 mg N kg⁻¹ soil (800, 1600 and 2400 mg N pot⁻¹, respectively).

Table 2.4. Amount of fertilizer applied (g pot⁻¹) and amounts (mg pot⁻¹) of P and K given in the factorial treatments (a). In (b) the amount of fertilizer applied (g pot⁻¹) and amounts (mg pot⁻¹) of N, P and K is presented for the reference treatments

(a)

Factors	Nitrogen								
	800 mg N pot ⁻¹			1600 mg N pot ⁻¹			2400 mg N pot ⁻¹		
Fertilizer	Amount, g	P, mg	K, mg	Amount, g	P, mg	K, mg	Amount, g	P, mg	K, mg
MBM	10	600	50	20	1200	100	30	1800	150
MBML	10	500	100	20	1000	200	30	1500	300
MBMPK	14	770	770	28	1540	1540	42	2310	2310
Y4PK	6.4	192	928	12.8	384	1856	19.2	576	2784
NK	4	0	560	8	0	1120	12	0	1680

(b)

Reference	Amount, g	N, mg	P, mg	K, mg
Control	0	0	0	0
PKI	4	80	200	720
PKII	8	160	400	1440
PKIII	12	240	600	2160

2.4. Plant management

The sowing took place on 20.07.2007, with 1 g (about 180 seeds) per pot sown. The relatively high sowing density was used for minimizing the risks of low germination. The Days After Sowing (DAS) is calculated from 20.07.2007 (Table 2.4.). The fertilizer was applied just before sowing to the five cm depth. Irrigation was conducted twice a week by gardeners. Between the third and the final cut (DAS 95-207), there occurred problems with the western flower thrips (*Frankliniella occidentalis* (Pergande)), against which biological control agents, predatory mites *Amblyseius cucumeris*, were successfully used. The thrips infestation was distributed randomly over the treatments.

Table 2.5. Time of sowing and harvesting the yield (both in dates and days after sowing (DAS)).

	Sowing	1st cut	2nd cut	3rd cut	4th cut	5th cut	6th cut
Dates	20.07.2007	21.08.2007	19.09.2007	23.10.2007	28.11.2007	09.01.2008	12.02.2008
DAS	0	32	61	95	131	173	207

2.5. Data measurement

The yield was cut manually with scissors at 2 cm height from soil surface, total of six times. The yield was hammer-milled and dried to air dry (65 °C for 48 hours) and weighed. After the experiment was conducted, analyses of the soil (pH, Ca, P, K, Mg,

S) and plant material (P, P soluble and K) were carried out by Viljavuuspalvelu OY (accredited by FINAS ISO/IEC 17025 standard). Milled plant material from all cuts and all replicates was mixed and one sample for each treatment analyzed, the soil sample was taken from mixture of all replicates, as well.

Phosphorus uptake was determined and phosphorus uptake efficiency (PUE) was calculated using Equation 2 (adapted from Salomonsson *et al.* 1994).

$$\text{PUE (\%)} = 100(\text{Xf} - \text{X0})/\text{Xr} , \quad (2.)$$

$\text{Xf} = \text{P yield (mg pot}^{-1}\text{) from fertilized pots,}$

$\text{X0} = \text{P yield (mg pot}^{-1}\text{) form unfertilized pots}$

$\text{Xr} = \text{P application rate (mg pot}^{-1}\text{).}$

Additionally, in order to determine the nutrient use efficiency, also the efficiency of applied nitrogen (NUE of N input) was calculated according the Equation 1 (see page 19), whereas the N content of ryegrass was calculated to be 24.8 mg kg⁻¹ dry matter (MTT 2006) and 500 mg total N kg⁻¹ soil was used as the original N content of the soil (Jeng & Vagstadt 2009).

2.6. Data analysis

Analyses of variance (ANOVA) were conducted according to the experimental design using SPSS ® version 16.0. Firstly, the full-factorial sub-design with five fertilizer types and three nitrogen levels was tested for linear response effects by using the GLM procedure (Appendix III). Statistically significant differences were tested for between fertilizers, between nitrogen levels and also the interaction N level*Fertilizer effect.

Secondly, One-Way ANOVA was conducted between all treatments (all four reference treatments included) within all six cuts as well as total dry matter yield of ryegrass; Tukey's test was used for comparing the means (Appendices IV-V).

3. Results

3.1. Ryegrass yields with different fertilizers and nitrogen levels

From full factorial analyses of the five fertilizers and the three nitrogen levels, it can be concluded, that the cumulative yields (total harvest) of Italian ryegrass grew together with nitrogen level used. The same applies to all fertilizers tested ($p < 0.001$) (Fig. 3.1.). No statistically significant interaction between Fertilizer effect and Nitrogen was detected, yields grew together with nitrogen level ($p = 0.069$). When it comes to Fertilizer effects, Y4PK resulted lower than MBMPK ($p < 0.019$), no significant differences were detected on other fertilizers.

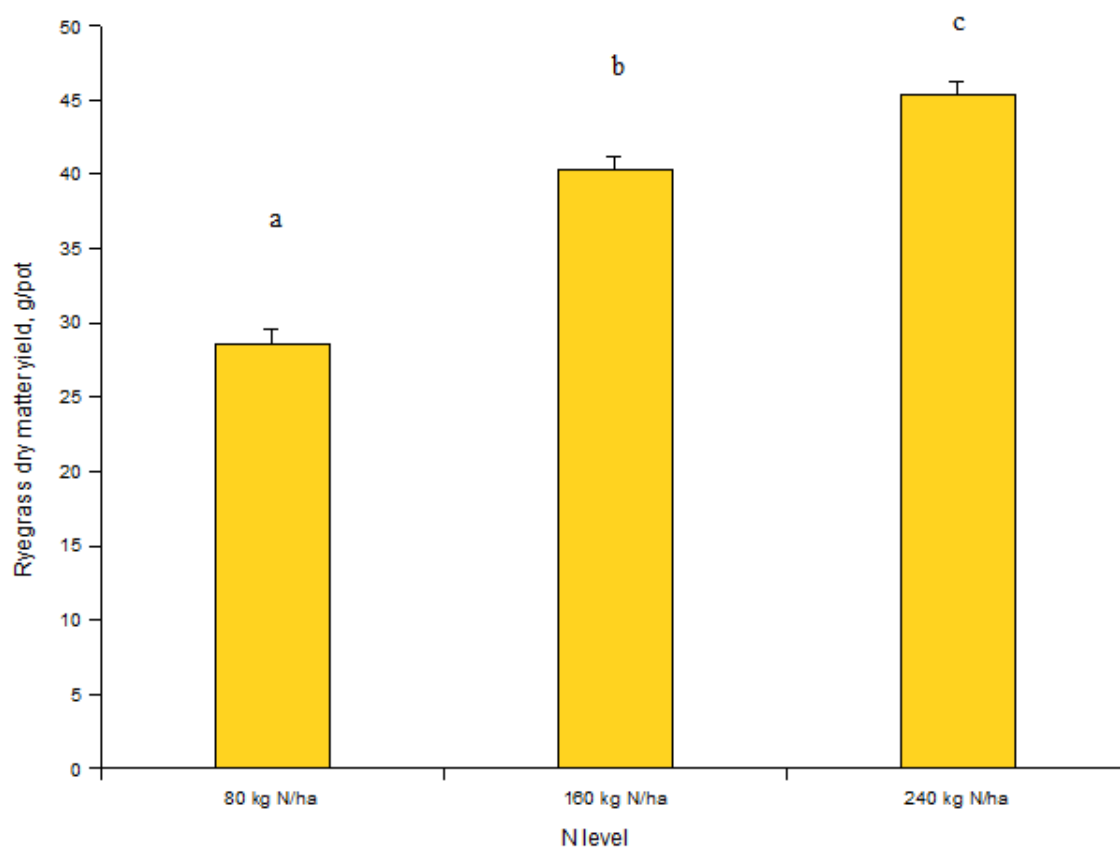


Figure 3.1. Ryegrass dry matter total yields in different nitrogen levels (error bars: deviance $n=20$). Means marked with the same lowercase letter did not differ significantly ($p < 0.05$), Tukey's test HSD.

From straightforward treatments comparison (One-Way ANOVA with all four reference treatments), there were no significant differences ($p < 0.05$) between the fertilizers found on two lowest nitrogen levels (Table 3.1., Appendix I). Nonetheless, all fertilizers resulted in significantly better total dry matter yield than the control. Additionally, there

were no significant differences between the fertilizers on the highest nitrogen level either, except NK, that gave significantly lower yield than MBMPK.

Table 3.1. Dry matter yield (g) of ryegrass, six cuts and total yield. Note that in addition to control (no fertilization), three levels of PK fertilizer are used as additional control (in order to demonstrate the phosphorus and potassium effect). DAS refer to Days After Sowing.

Treatment	1st cut	2nd cut	3rd cut	4th cut	5th cut	6th cut	Total
(kg N ha ⁻¹)	32 DAS	61 DAS	95 DAS	131 DAS	173 DAS	207 DAS	
Control	5.63 a	2.30 a	1.30 a	1.97 a	1.09 a	2.71 a	15.00 a
PK I	7.28 ab	2.79 ab	1.51 a	1.75 a	1.41 a	2.9 a	17.43 ab
PK II	8.13 abc	5.76 abcd	1.60 a	1.89 a	0.78 a	2.98 a	21.12 abc
PK III	10.74 bcde	4.11 abc	1.61 a	2.27 ab	1.28 a	2.66 a	22.66 abc
MBM							
80	9.85 bcd	5.36 abc	3.18 ab	2.89 abc	1.95 ab	3.14 a	26.37 bc
160	13.57 de	8.57 cdef	5.14 bcd	4.69 def	3.26 bcd	5.23 c	40.46 fg
240	14.15 e	12.10 efgh	5.07 bc	5.37 efg	4.00 de	4.95 bc	45.64 fgh
MBML							
80	9.70 bcd	5.02 abc	3.22 ab	3.16 abcd	2.23 abc	3.47 a	26.79 bcd
160	12.04 de	7.34 bcde	5.29 bcde	4.99 efg	3.60 cde	5.24 c	38.50 efg
240	12.81 de	11.82 efgh	6.62 cde	6.65 gh	4.37 de	5.21 c	47.47 gh
MBMPK							
80	11.69 cde	5.60 abcd	3.60 ab	3.30 abcd	2.00 ab	3.50 a	29.68 cde
160	11.77 cde	10.21 defg	7.34 cde	6.05 fgh	4.03 de	5.98 c	45.38 fgh
240	12.78 de	12.20 fgh	7.84 de	7.57 h	4.90 e	5.06 c	50.43 h
Y4PK							
80	12.90 de	7.57 bcdef	3.39 ab	1.88 a	1.36 a	2.89 a	29.99 cde
160	10.39 bcde	11.08 efgh	5.81 bcde	3.72 bcde	1.65 a	3.57 a	36.21 def
240	11.44 cde	15.01 h	7.04 cde	4.61 def	1.74 a	3.19 a	43.02 fgh
NK							
80	11.69 cde	7.81 cdef	3.64 ab	2.65 ab	1.21 a	3.37 a	30.35 cde
160	10.52 bcde	13.40 gh	7.11 cde	4.55 cdef	1.65 a	3.76 ab	40.99 fgh
240	10.29 bcde	12.17 fgh	7.88 e	4.34 cde	1.99 ab	3.55 a	40.21 fg

Within a column, values followed by the same lowercase letter do not differ significantly ($p < 0.05$), Tukey's test HSD.

Two of the higher application levels of MBMPK resulted in the highest (although not statistically significantly) yields. In case of two higher application rates of PK, the total yields were not significantly different from the lowest N level of other fertilizers.

When it comes to the duration of fertilizer effect, most of the cuts' ryegrass yields between mineral fertilizer (Y4PK) and meat bone meal did not differ at any nitrogen level. Anyhow, on 5th and 6th cut MBM yielded even higher than Y4PK (at two higher nitrogen levels, ($p < 0.05$), Tukey's test HSD) (Table 3.1. and Figure 3.2.). The relative fertilizer effect of MBM in comparison to Y4PK on three N levels was highest on medium N level (160 kg N ha⁻¹), reaching to 111.7% of Y4PK effect (Appendix II).

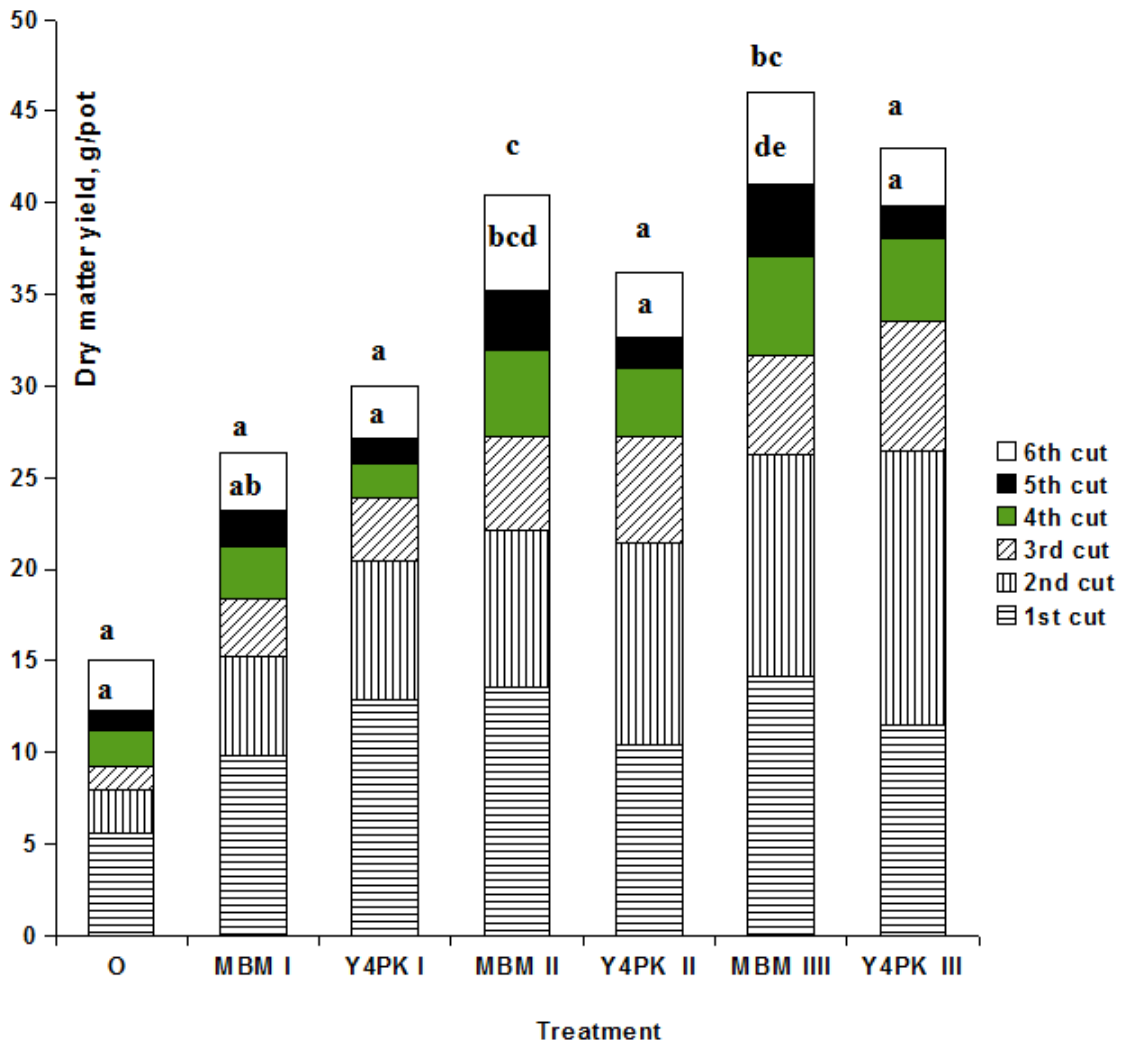


Figure 3.2 Ryegrass dry matter yields with control, MBM and Y4PK; contribution of six cuts presented. Roman numbers represent three nitrogen levels (80, 160 and 240 kg N ha⁻¹, respectively). In case of 5th and 6th cut, within a cut, columns marked with same lowercase letters do not differ significantly ($p < 0.05$), Tukey's test HSD.

3.2. Plant and soil nutrient contents and nutrient use efficiency

Post-harvest comparisons of the nutrient content of ryegrass plant materials revealed marked differences between treatments. Plants fertilized with MBM contained more phosphorus (and also soluble phosphorus) and less potassium than those fertilized with

Y4PK (Table 3.2.). The lowest resulted plants fertilized with NK- their nutrient contents were even lower than the control.

Table 3.2. Post-harvest plant nutrient content (g kg^{-1} dry matter) and nutrient use efficiencies. PUE refers to phosphorus uptake efficiency; NUE of N input refers to nitrogen uptake efficiency from N input.

Treatment (kg N ha^{-1})	P	K	P (soluble)	PUE, %	NUE of N input, %
Control	4.37	38	4.3		
PK I	4.4	41	4.4	3.86	3.29
PK II	4.7	43	4.4	6.89	7.95
PK III	4.7	40	4.6	5.94	9.55
MBM					
80	4.8	28	4.5	8.85	11.06
160	5	29	4.6	10.60	18.85
240	5	26	4.7	8.61	18.31
MBML					
80	4.3	36	4.2	8.42	11.47
160	4.3	37	4.2	9.18	17.40
240	4	40	4.1	7.82	19.40
MBMPK					
80	4.5	40	4.4	7.91	14.28
160	5	45	4.2	9.90	22.49
240	5	33	5	7.78	21.17
Y4PK					
80	4.1	45	3.7	20.38	14.58
160	4.5	51	3.9	20.56	15.70
240	4.3	52	4	17.94	16.74
NK					
80	3.7	36	3.4	51.99	14.93
160	3.7	33	3.4	95.74	19.24
240	4	44	3.6	105.93	15.07

The highest phosphorus uptake efficiency (PUE) was in case of NK. Next resulted Y4PK, with PUE approximately twice as high as MBM. It should be noted, that generally the highest PUE was in case of medium N level.

The efficiency of nitrogen input of MBM was higher than Y4PK in case of two higher N levels, on the lowest level the opposite was the case. Overall the lowest NUE of N input was in case of PK controls and highest in case of MBMPK.

Post-harvest comparisons of the nutrient content of soils used in the experiment indicated differences between treatments- soils fertilized with MBM contained remarkably more phosphorus and calcium than Y4PK (Table 3.3.).

Table 3.3. Results of soil analyses after the experiment was conducted. Minerals content is given in mg l⁻¹ soil. Min. Sat. refers to minimal level for being “satisfactory” (Viljavuuspalvelu 2008).

Treatment (kg N ha ⁻¹)	pH	Ca	P	K	Mg	S
Control	6.4	1133	22.0	54.0	98.3	17.0
PK I	6.4	1100	24	100	100	21
PK II	6.2	860	29	170	100	19
PK III	6.2	920	33	200	99	25
MBM						
80	6.5	1400	55	28	95	18
160	6.3	1400	83	29	83	18
240	6.3	1700	140	30	85	22
MBML						
80	6.3	1400	47	31	99	19
160	6.3	1400	73	31	94	22
240	6.1	1500	100	29	85	38
MBMPK						
80	6.3	1300	49	44	100	25
160	6.1	1300	110	56	110	36
240	5.8	1400	120	80	110	11
Y4						
80	6.2	1000	25	49	94	21
160	5.8	910	32	88	87	32
240	5.6	810	33	110	80	58
NK						
80	6.3	1200	20	30	94	20
160	5.9	810	20	33	72	27
240	5.8	870	22	42	69	41
Min. Sat.	5.8	1400	9	120	120	10

While in case of phosphorus, Y4PK resulted still more than “satisfactory” (Viljavuuspalvelu 2008), calcium level was below that limit in all three nitrogen levels. Y4PK, as a mineral fertilizer, also lowers the pH of the soil, even below the “satisfactory” level in case of third N level. In addition to that, it should be pointed out that both the K and Mg content of the soil were lower than “satisfactory” level in case of almost all the treatments.

4. Discussion

4.1. Ryegrass yields with different fertilizers and nitrogen levels

Fertilizer type effect

The yield of agricultural products grown using organic fertilizers is generally recognized as being significantly lower than the yield gained with mineral fertilizers. According to Eltun *et al.* (2002), the average grassland yields from ecological farming systems were 7-22% lower than in conventional systems in an eight-year comparison in Norway. Offermann & Nieberg (2000) report 5-21% lower grassland yields in organic farms than their conventional counterparts in Sweden and Norway. The main reason for such a difference might be related to commonly slower mineralization rates of organic fertilizers having so the most vivid difference in northern regions, where the growth period is shorter.

However, in the present study, no statistically significant differences between fertilizers were found. The only exception was NK that gave significantly lower yield than MBMPK on the highest nitrogen level. As there were no statistically significant differences found in cumulative yield effects in any nitrogen level between MBM and mineral Y4PK fertilizer, such results are in concert with findings from previous MBM research in Scandinavian countries with cereals and ryegrass (Salomonsson *et al.* 1994, 1995, Jeng *et al.* 2006, Chen L. 2008). Moreover, in the present study, on two higher application levels the fertilizing effect of MBM lasted even longer than mineral fertilizers (Y4PK and NK).

On the other hand, there is also evidence that the fertilizing effect of MBM is significantly lower than mineral fertilizers, yet reaching from 81% in case of spring wheat (Jeng *et al.* 2004) to 96% in case of oats (Kivelä 2007).

Nevertheless, all the aforementioned research agrees that MBM is a highly efficient organic fertilizer with fertilizing effect being at least 80% of the mineral nitrogen fertilizers. Such a strong effect compared to alternative organic fertilizers might be due to high content of plant-available nutrients (27-29% of dry matter) (Kivelä, 2007) and relatively fast mineralization of organic forms of nitrogen (Mondini *et al.* 2008). The latter is partly attributable to considerably low (about 4) C/N ratio of MBM (Brady & Weil 2002, p. 505-511, Jeng *et al.* 2004). Mondini *et al.* (2008) report a remarkable increase in both extractable NH_4 and NO_3 (about 50% of added N), together with enhanced microbial content and activity in soil caused by MBM application.

According to Brady & Weil (2002, p. 505-511), the low C/N ratio of organic fertilizer results in high microbial activity, rapid decomposition of added organic compounds and increased levels of plant-available nitrogen. Additionally, the low C/N ratio of a fertilizer contributes to intensified mobilisation of nutrients from soil organic matter (Rajala 2004, p. 136).

The phosphorus content of MBM is relatively high (varying from 5 to 9%), whereas readily plant available fraction contributes 19-40% (Jeng *et al.* 2004, 2006, Ylivainio *et al.* 2008, Ylivainio & Turtola, 2009). Ylivainio *et al.* (2008) compared the P availability of MBM, superphosphate (SP), and cow manure in a 3-year pot experiment with ryegrass. MBM-P immediately available to plants contributed only 19 % of the availability of P from SP and dairy manure, however for the 3-year period with ten ryegrass cuts, the P availability of MBM increased to 63 % (Ylivainio *et al.* 2008). According to Kivelä (2007), MBM can sustain the soils fertility in terms of P demand, even though the importance of phosphorus fertilization is not crucial in terms of yield effects (unless serious P deficiency exists in the soil).

Nitrogen level effect

The average nitrogen application level in agricultural soils in Finland is approximately 90 kg ha⁻¹ (Antikainen *et al.* 2005), but it should be noted that the most efficient application rate of fertilizers depends largely on soil and climate conditions as well as on plant and fertilizer type.

In comparison with five fertilizers in present study, the ryegrass dry matter yields grew together with nitrogen level used, being the highest at N level of 2400 mg N pot⁻¹ (240 kg N ha⁻¹). Such a result is coherent with the outcome of the field experiment reported by Kivelä (2007), where oats yields from fertilization with both mineral fertilizer and MBM differed significantly between N rates of 60, 90 and 120 kg ha⁻¹.

On the other hand, Jeng *et al.* (2004) found no significant differences between wheat yields with MBM application levels of 100 and 200 kg N ha⁻¹. Furthermore, no significant differences in barley yields were detected between MBM-N rates of 117 kg ha⁻¹ and 234 kg ha⁻¹ (Jeng *et al.* 2006). Additionally, it should be noted that the relative fertilizer effect of MBM in comparison to Y4PK on three N levels was highest on medium N level (160 kg ha⁻¹), reaching to 111.7% in present study

The yield response to applied nitrogen amount is largely dependent on the soils' plant-available nitrogen content. According to Jeng *et al.* (2006), large amounts of

plant-available soil nitrogen, some of it present in the soil in spring and some released by mineralization during the growing season, may influence the crops need of nitrogen released from MBM. Generally the effect of MBM is largest on soils with low content of soil organic matter (SOM) and low supply of N mineralized from SOM. On the other hand, excessive nitrogen supply cannot be completely used by plants. As the soil's organic matter content was rather low in present study, the medium N level (160 kg N ha⁻¹) might have been the optimal level for MBM-N fertilization.

The yield effect of a mixture of MBM and a high potassium content fertilizer

MBM is a highly effective organic alternative for mineral nitrogen and phosphorus fertilizers. However, the potassium content of MBM is rather low (0.5%) and thereby the demand for additional potassium fertilizer is exists on most agricultural soils. There is not much previous research available of the yield effects of MBM based fertilizers in mixture with high K containing fertilizers.

Anyhow, in present research, both such mixtures (MBMPK and MBML) resulted among the highest dry matter yield of all fertilizers, even though the differences from others were not statistically significant. Thereby the fertilizing potential for mixture of meat bone meal and potassium fertilizers is rather high, yet the lack of potassium sources usable in organic agriculture should be noted. In addition to potato liquid extract used in this experiment, biotite and potassium sulphate could be used as other possible alternatives (Rajala 2004, p. 322, Stamford *et al.* 2006, Elosato 2009). Additional research is needed in order to find ways for improving MBM as NPK fertilizer, and possible alternatives for the mineral PK fertilizer should be looked for.

4.2. The nutrient uptake efficiencies and changes in soil fertility

The nutrient uptake efficiencies

The nutrient uptake efficiencies are at highest agronomical importance to advance in the design of crop management schemes that amplify nutrient efficiency and reduce the need of fertilizers.

The extremely high phosphorus uptake efficiency (PUE) of non-P containing NK treatment can be explained by amplified mobilization of P from soil stocks with the contribution of ryegrass roots. According to Jones (1998), the lack of phosphorus can increase the production of organic acids from the roots, amplifying consequently the growth and activity of micro-organisms in the rhizosphere (Toal *et al.* 2000). The

increased microbial activity in the rhizosphere may result in augmented organic phosphorus content in the NaHCO_3 - (Chen *et al.* 2002) and NaOH-extractable fractions (Zoysa *et al.* 1999). The former fraction is reported to be contributing to plant-available P pool in case of lack of mineral phosphorus in soil (Guo *et al.* 2000).

The nutrient uptake efficiency of MBM fertilization has been previously studied in terms of nitrogen uptake efficiency (NUE) (Salomonsson *et al.* 1994, 1995, Jeng *et al.* 2004) and phosphorus uptake efficiency (PUE) (Ylivainio *et al.* 2008, Ylivainio and Turtola 2009). The NUE of MBM-N is reported to range from 13% to 22% in case of winter wheat, whereas the mineral counterpart resulted in 17% and 24%, respectively (Salomonsson *et al.* 1995). Jeng *et al.* (2004) show NUE of MBM-N to be 11-18% in case of barley as mineral counterparts resulted in 29-38%. Those results are in concert with findings of present study, where the efficiency of nitrogen input was found to be 11-19% in case of MBM and 15-17% in case of Y4PK.

On the other hand, there is evidence of significantly higher nitrogen uptake efficiencies of MBM-N, as well. In case of spring wheat, NUE of meat bone meal is reported to range from 25 to 42%, whereas mineral fertilizers resulting only slightly better- from 32% to 43% (Salomonsson *et al.* 1994, Jeng *et al.* 2004). Such a variation can be partly explained by differences in the C/N ratio of growth media, as its high C/N ratio is reported to result in higher immobilization of applied nitrogen (Jeng *et al.* 2004). Additionally, in present study, the difference is partly attributable to the use of constant N contents for plants and soils in calculating the NUE of N input. Conducting N content analyses would have made the results more valid and thereby also more comparable.

When it comes to phosphorus uptake efficiency of MBM-P, it is generally recognized as being lower than the PUE of mineral fertilizers. In present study, that was the case as well- PUE ranged between 9-11% in case of MBM and 18-21% in case of Y4PK. Such result is consistent with data of Ylivainio and Turtola (2009), where PUE of MBM was 13% in first year, whereas for mineral superphosphate, it was 23%. The P application level in Ylivainio and Turtola (2009) ryegrass pot experiment was similar to the lowest application rate in present study (60 kg P ha^{-1}).

Such divergence can be explained by lower readily plant-available phosphorus content of MBM than mineral phosphate fertilizers. However, a significant amount of MBM-P is still available for following years, as the differences in yields in pot experiment with ryegrass levelled off by third experimental year, being 63% of superphosphate efficiency (Ylivainio *et al.* 2008, Ylivainio and Turtola 2009). In case of grassland field trials, the relative phosphorus efficiency of MBM was even 100% of

superphosphate efficiency after three to four years (Ylivaino and Turtola 2009). Similarly, Jeng *et al.* (2006) show that the P in MBM had residual effect the year after application- the field experiments with spring wheat showed no additional need for P when at least 500 kg MBM ha⁻¹ was applied.

The highest nutrient use efficiencies of both MBM nitrogen and phosphorus on the medium application level (160 kg N ha⁻¹) can be explained by the most balanced nutrient situation in soil. It seems that on this application level, there is the least excessive nitrogen and phosphorus and the deficiency of potassium is not yet limiting the growth of ryegrass. This is also coherent with the law of minimum, stating that the availability of the most abundant nutrient in the soil is depends on the availability of the least abundant nutrient in the soil. Similarly, Jeng *et al.* (2004) found higher NUE in case of 180 kg N ha⁻¹ than 60 kg N ha⁻¹ in case of barley.

Changes in soil quality

The post- harvest soil analyzes provide useful data for distinguishing the changes in soil fertility, illustrating so the shortcomings of fertilization.

The residual effect of MBM-P was clearly evident as the P content in post-harvest soils is excellent in all application levels. The somewhat increased soil P level for all treatments can be explained by mobilization of P stocks from soil by increased microbial activity in the rhizosphere in case of low P treatments. However, for majority of treatments, the greatest influence was probably due to relatively high P application levels.

The negligible potassium content of the post-harvest soil for all treatments except two higher level of PK control illustrates clearly the relatively high K demand of ryegrass and consequently, need for additional potassium fertilization. The same applies to magnesium, as all treatments lowered the soil's original Mg level below the satisfactory level.

The present study showed that in addition to better residual effect of MBM-P, MBM results also in higher Ca content as well as higher pH of the soil than mineral fertilizer, Y4PK. Therefore, it can be concluded that the relatively high Ca content of MBM (11-15%) is useful in preventing extra costs for liming the soil that would be needed if mineral fertilizers would be used.

4.3. Practical considerations of MBM use

The nutrient content of MBM (8-6-1) does not correspond to nutrient requirements of plants, mainly because of narrow N/P ratio and low K content of MBM. The N/P ratio of MBM is considerably narrower than the normal nutrient uptake ratio of cereals, resulting in P addition in soils on levels of environmental concern in case of annual application of MBM. For that reason, it is recommended that if MBM is used to meet the N demand of the crops, P application for the following year (or even for the whole crop rotation) should be omitted (Kivelä *et al.* 2005, Jeng *et al.* 2006). The potassium content of MBM is rather low (0.5%) and on most agricultural soils, the demand for supplementary potassium fertilizer exists. In organic farming, some of the most viable alternatives for additional K are biotite and potassium sulphate (Rajala 2004, p. 322, Stamford *et al.* 2006, Elosato 2009).

The growth conditions affect significantly the fertilizer effect of MBM, as the MBM nutrients need to be mineralized from organic form. The growth medium together with water availability is largely affecting mineralization of MBM nutrients. Dry clay soils are unsuitable, and the same applies to peat soils (Gruvaeus 2002 ref. Kivelä 2007, Jeng *et al.* 2004). The availability of MBM nutrients was significantly poorer on clay soils (and the effect was underlined even more during dry growing periods) as shown by a field study conducted in Sweden (Gruvaeus 2002 ref. Kivelä 2007). In case of peat, the high C/N ratio of it results in high immobilization of MBM-N in case of lower application rates (Jeng *et al.* 2004).

The application of meat bone meal to fields depends largely on the structure of it. The granulated MBM can be applied either by drill or by broadcasting, using mineral spreaders. The meal type fertilizer, on the other hand, can be applied most efficiently by the use of wet liming equipment (Kivelä *et al.* 2005). Finnish organic farmers participating in field trials of MBM fertilization in years 2003 and 2004 used mostly wet and dry liming machinery for meal type MBM application (Kivelä *et al.* 2005). As the greatest practical problem they noted was caking of the fertilizer, the alternatives tried (mineral spreaders or manure spreaders) were not viable (Kivelä *et al.* 2005).

The Finnish MBM producer Honkanjoki OY has developed further series of granulated organic fertilizers, which, in mixture with potassium sources, provide plant nutrients in more balanced combination than mere MBM (product website: <http://www.elosato.fi/index.html>). Those MBM- based granulated fertilizers are recommended to be applied by mineral spreader to either ploughed or cultivated field

directly before sowing (Elosato, 2009). An alternative for immediate sowing would be instant cultivation of the soil, so that the applied fertilizer would be covered with 5-10 cm of soil. Consequently, the soil-covered fertilizer will moist and gradual release of nutrients available for micro-organisms and plants will take place. The use of such practice makes possible to postpone the sowing even for several weeks yet the nutrients are present and available for plants instantly after sowing (Elosato 2009).

According to some research, the MBM application is suggested to be divided into two during one growth period. Salomonsson *et al.* (1994) report that application of MBM fertilization partly before sowing and partly at growth stage 30-31 increased the protein content of spring wheat yield. The main shortcoming of this approach is possible physical damage caused to crops by machinery used for fertilizer broadcasting.

Some of the farmers participating in MBM fertilization experiment in Finland in years 2003 and 2004 noted the problem of dust and smell with MBM (Kivelä *et al.* 2005). The human sensitivity to such problems is greatly individual and there is not much evidence of allergic reactions caused by meat bone meal dust. However, Diaz-Jara *et al.* (2001) report a case of allergic reaction and occupational asthma caused by inhalative exposure to cow bone dust of a young butcher. Similarly, Huhtanen *et al.* (2007) report another case of occupational asthma for a worker of Finnish MBM production plant, who was exposed to MBM dust daily. It is suggested to use effective respirators while exposed to dust from meat bone meal and if allergic reactions occur, the person should avoid direct exposure to MBM (Huhtanen *et al.* 2007). Additionally, the granulation of meat bone meal fertilizers is expected to reduce significantly the dust-related problems.

The economics of MBM fertilization are discussed in Kivelä *et al.* (2005) and in Kivelä (2007). The additional yield and higher protein content of the yield with the use of relatively low-priced MBM is found to keep fertilizer use of MBM economically viable, especially in organic farms. Possible increases in crude oil prices will raise also the price of mineral fertilizers, this together with gradually growing prices of organic foodstuff show promising perspective for the fertilizer use of MBM.

5. Conclusion

The results of this experiment showed that meat and bone meal (MBM) is a highly efficient N and P fertilizer in case of ryegrass with fertilizing effect similar or even longer lasting than mineral Y4PK fertilizer. Additionally, as the meat and bone meal is an industrial by-product that contains nutrients originating from agriculture, its fertilizer use contributes into closing the nutrient cycle. Consequently, higher sustainability of agricultural systems could be achieved.

The nutrient uptake efficiencies of MBM were generally lower than for mineral counterparts. That could be partly attributable to possible higher immobilization of applied MBM-N to soil and partly because of lower readily plant-available phosphorus content of MBM than mineral phosphate fertilizers. However, as significant amount of MBM-P is still available for following years, it is justified to use MBM only once in an organic crop rotation.

Unlike mineral fertilizer Y4PK and NK, meat and bone meal treatments did not lower the pH level of the soil. Therefore, it can be concluded that the relatively high Ca content of MBM (11-15%) is useful in preventing extra costs for liming the soil that would be otherwise needed.

The potassium content of MBM is rather low (0.5%) and thereby the demand for additional potassium fertilizer exists on most agricultural soils. The fertilizing potential for mixture of MBM and K fertilizers was shown to be rather high, but the lack of potassium sources suitable for organic agriculture might be problematic. Additional research is needed in order to find ways for improving MBM as NPK fertilizer.

All in all, MBM is a highly effective organic source for nitrogen and phosphorus and its use is especially recommended in organic crop rotations- the phosphorus fertilization effect lasts from two to four years. Additionally, as MBM nutrients originate from agriculture, the fertilizer use of MBM helps to close the nutrient cycle in the food system.

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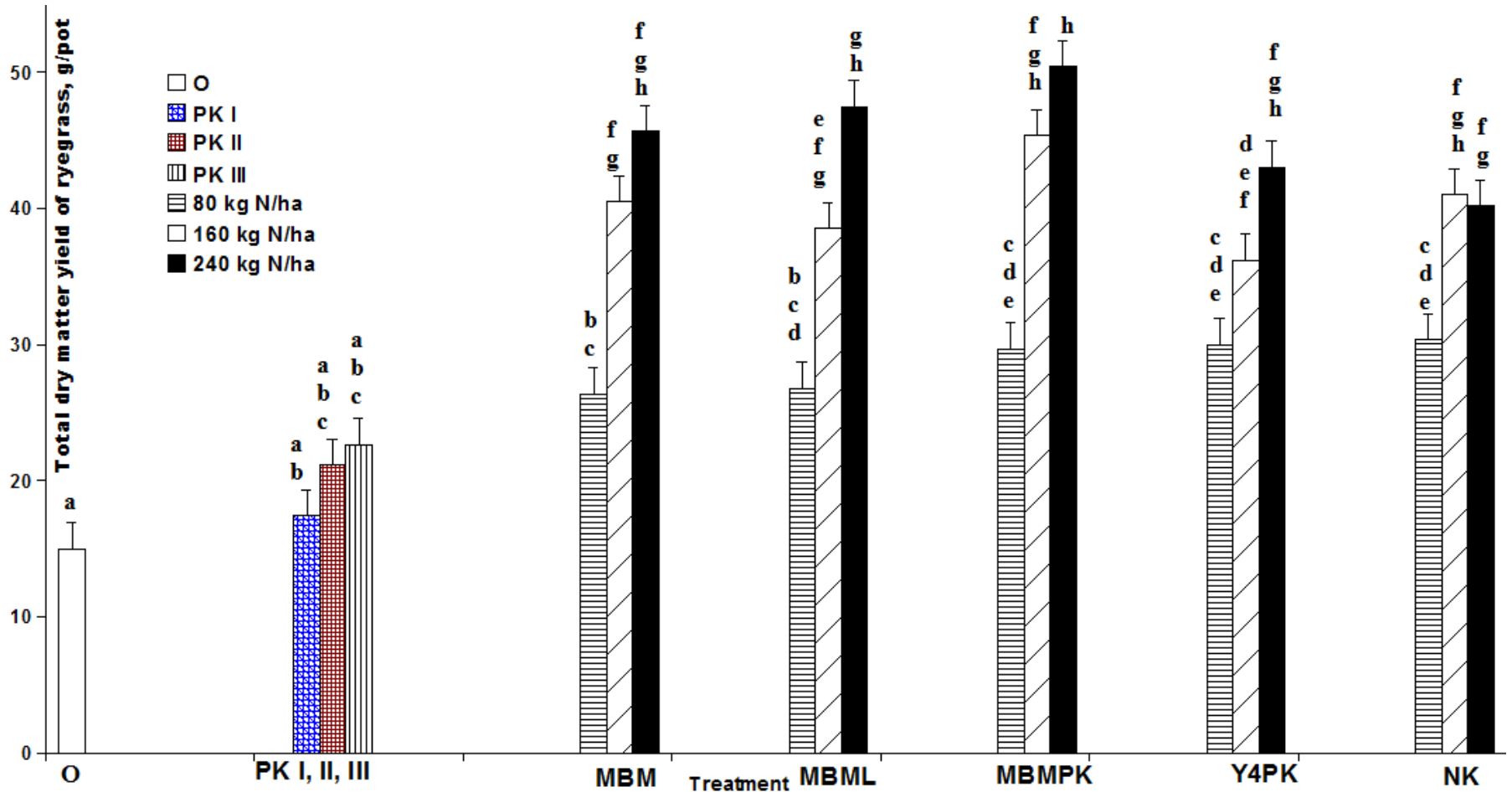
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APPENDIX I: Comparison of different fertilizers in ryegrass total yields. Columns marked with same lowercase letters do not differ significantly ($p < 0.05$), Tukey's test HSD.



APPENDIX II: Comparison of cumulative DM yields of other treatments with Y4PK, relative and absolute difference.

Treatment		Total yield, g	% of Y4	Difference from Y4, g
80 kg N/ha	Control	15.00	50.0	-14.99
	PK I	17.43	58.1	-12.56
	PK II	21.12	70.4	-8.87
	PK III	22.66	75.6	-7.33
	MBM	26.37	87.9	-3.62
	MBML	26.79	89.3	-3.20
	MBMPK	29.68	99.0	-0.31
	Y4PK	29.99	100.0	0.00
	NK	30.35	101.2	0.36
160 kg N/ha	Control	15.00	41.4	-21.21
	PK I	17.43	48.1	-18.78
	PK II	21.12	58.3	-15.09
	PK III	22.66	62.6	-13.55
	MBM	40.46	111.7	4.25
	MBML	38.50	106.3	2.29
	MBMPK	45.38	125.3	9.17
	Y4PK	36.21	100.0	0.00
	NK	40.99	113.2	4.78
240 kg N/ha	Control	15.00	34.9	-28.02
	PK I	17.43	40.5	-25.59
	PK II	21.12	49.1	-21.90
	PK III	22.66	52.7	-20.36
	MBM	45.64	106.1	2.62
	MBML	47.47	110.3	4.45
	MBMPK	50.43	117.2	7.41
	Y4PK	43.02	100.0	0.00
	NK	40.21	93.5	-2.81

APPENDIX III: Total ryegrass dry matter yield, five fertilizers (MBM, MBML, MBMPK, Y4PK and NK)

Tests of Between-Subjects Effects

Dependent Variable:DMY

Source	Type III Sum of Squares	df	Mean Square	F	P-value
FERT	219,305	4	54,826	3,210	,021
Nlevel	2941,930	2	1470,965	86,117	,000
FERT * Nlevel	272,830	8	34,104	1,997	,069
Error	768,643	45	17,081		
Total	91289,402	60			
Corrected Total	4202,708	59			

a. R Squared = ,817 (Adjusted R Squared = ,760)

APPENDIX IV: Ryegrass dry matter yields, cuts 1-3**Tests of Between-Subjects Effects**

Dependent Variable:DMY

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
FERT (1st cut)	539,587	18	29,977	12,842	,000
Error	151,735	65	2,334		
Total	9794,035	84			
Corrected Total	691,322	83			

a. R Squared = ,781 (Adjusted R Squared = ,720)

Tests of Between-Subjects Effects

Dependent Variable:DMY

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
FERT (2nd cut)	1303,616	18	72,423	20,394	,000
Error	230,833	65	3,551		
Total	6708,071	84			
Corrected Total	1534,450	83			

a. R Squared = ,850 (Adjusted R Squared = ,808)

Tests of Between-Subjects Effects

Dependent Variable:DMY

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
FERT (3rd cut)	454,148	18	25,230	22,150	,000
Error	74,040	65	1,139		
Total	2096,780	84			
Corrected Total	528,188	83			

a. R Squared = ,860 (Adjusted R Squared = ,821)

APPENDIX V: Ryegrass dry matter yields, cuts 4-6**Tests of Between-Subjects Effects**

Dependent Variable:DMY

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
FERT (4th cut)	240,636	18	13,369	30,699	,000
Error	28,306	65	,435		
Total	1434,569	84			
Corrected Total	268,942	83			

a. R Squared = ,895 (Adjusted R Squared = ,866)

Tests of Between-Subjects Effects

Dependent Variable:DMY

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
FERT (5th cut)	125,979	18	6,999	21,475	,000
Error	21,184	65	,326		
Total	561,371	84			
Corrected Total	147,163	83			

a. R Squared = ,856 (Adjusted R Squared = ,816)

Tests of Between-Subjects Effects

Dependent Variable:DMY

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
FERT (6th cut)	90,450	18	5,025	22,358	,000
Error	14,609	65	,225		
Total	1280,392	84			
Corrected Total	105,059	83			

a. R Squared = ,861 (Adjusted R Squared = ,822)