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Fertilizing for High Yield and Quality

Oilseed Rape

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1. Introduction

Domestication of members of the Brassica family to oil producing crops occurred during different periods of history and in many locations throughout the world. In the old civilizations of Asia and the Mediterranean, rape oil was used for lighting purposes. Rape crops were cultivated in India 3000 years ago and were introduced to China and Japan about 500 to 200 BC (Krzymanski, 1998). In Europe, seeds and pods have been recovered from excavations of Bronze Age sites.

Because of high prices for animal fat, the poorer population in particular had to use rape oil not only for lighting but also as a source of their nutrition. With the development of mineral oil and the worldwide marketing of petroleum, however, the importance of rape oil as a fuel decreased. Today oilseed rape is cultivated and processed for many different purposes: oil for human nutrition, as a renewable raw material for the chemical industry, as a source of regenerative energy, as a source of high energy and protein content for animal nutrition in the form of rape cake and meal, as a catch crop for green manuring and as a forage crop. The importance of rape has thus increased in recent years and today it is cultivated on every continent.

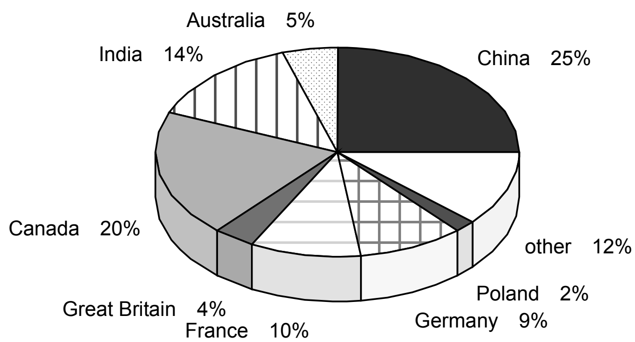

Fig. 1. Most important countries for oilseed rape production (FAO).

1.1. Acreage and production of oilseed rape

World production of oilseed rape has increased very rapidly over the last 20 years. China with 25% of world production is the largest producer of oilseed rape with nearly 10 million t/year (Fig. 1). India is also an important producer of oilseed rape accounting for as much as 14% of world production. However, although both these countries together produce almost 40% of world production only a small quantity of this is sold on the world market since nearly all of it is used for home consumption.

In the countries of the northern hemisphere with cool and humid climates oilseed rape is a very important oil- and protein-crop. No other crop under these climatic conditions produces such high yields of both oil and protein. Thus Canada (20% of the world production) and the European countries, Germany, France, and the UK are among the main producers of oilseed rape. Canada in particular is the main exporting country on to the world market. Compared with 20 years ago, there has been an impressive increase in rate of annual production by over 200% in nearly all important oilseed rape producing countries. This rise in production is not only the consequence of an increasing area of crop cultivation (Fig. 2) but also of higher yields per unit area (Fig. 3).

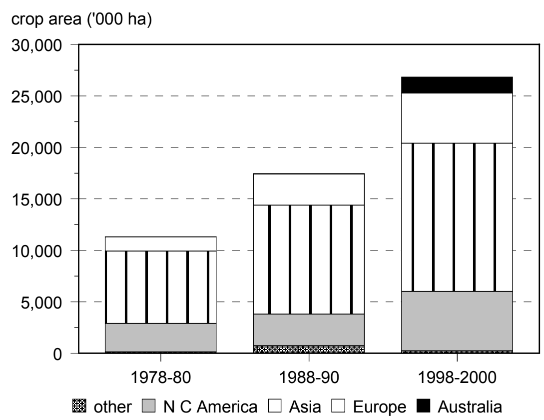

Fig. 2. Development of the world oilseed rape cultivation area (FAO).

The average yield of oilseed rape depends on climate, soil fertility, intensity of production, fertilizer input, species and variety of rape crop. The average yields thus show a wide range from country to country (Fig. 3). The average world yield has increased over 50% from nearly 0.9 t/ha to 1.5 t/ha during the last 20 years (+2.9% per year). With the exception of the African continent and the former USSR in all other countries a significant yield increase has been observed particularly over the last decade. The high yields found in European countries (for example 3.5 t/ha in Germany) are generally based on high production standards together with favorable climatic conditions allowing the use of high-yielding winter types of oilseed rape together with a high fertilizer input. In Canada and parts of Asia, yields are lower because of low fertilizer inputs and of hard winters permitting cultivation of only spring type varieties. In other countries, yields might be increased using improved varieties, irrigation and advanced farming technology combined with optimum fertilizer use.

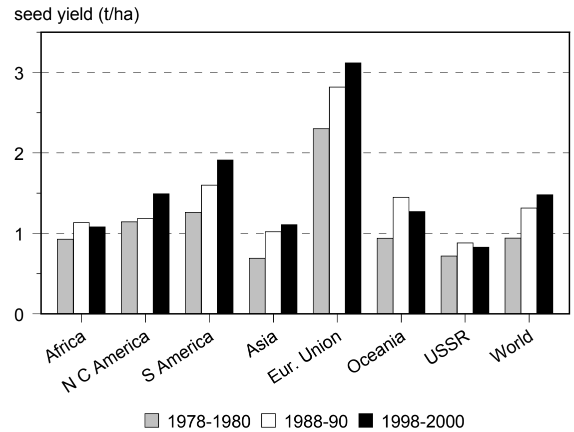

Fig. 3. Development of average seed yields of oilseed rape in various regions of the world (FAO).

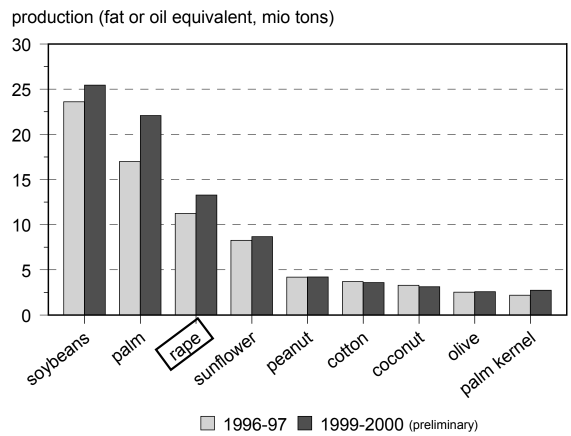

Fig. 4. World vegetable oil production 1996-97 and 1999-2000 as fat or oil equivalent (USDA).

Within the vegetable oils, rape oil is very important because of its high oil content of about 40%. The global production of edible oils has increased over the last 4 years from 76 to 86 million metric tons (+13%). Soybean oil makes up the largest proportion (30%) of production followed by palm oil (26%). Oilseed rape is in third place with 15% of world production (Fig. 4) indicating the high value of the seeds as a source for oil and animal feed. The increase of world production of vegetable oil has been largely dependent on the greater production of palm oil, oilseed rape and soybean.

The high quality of oilseed rape oil has also been expressed in its comparatively high oil price. The value of vegetable oils has increased significantly in recent years until 1998. Only in the last two years has a sharp decrease been observed. However, future price estimations are optimistic, so that further increases in rape cultivation are to be expected.

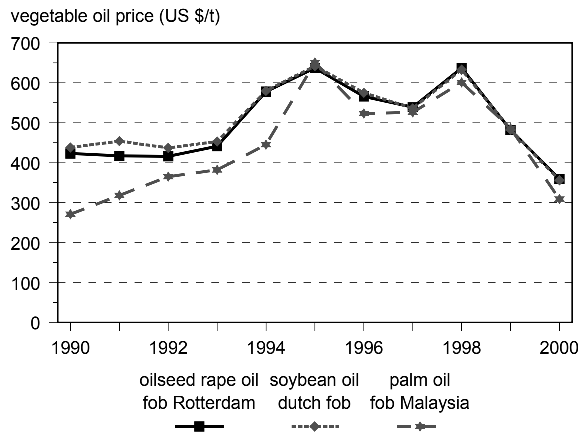

Fig. 5. Changes of price for some important vegetable oils over the last 10 years (USDA).

2. Botany

On the world market, the general term ‘rape’ comprises oil seeds of different plant species. All of these species are derived from the Brassica genus and the Cruciferae family. In this family, numerous other species are combined (for example *B. kaber, B. elongata, B. oleracea* with many subspecies). The chromosome number varies for the different species within the Brassica genus (Fig. 6). The species *B. campestris, B. oleracea and B. nigra* are diploid whereas *B. napus, B. carinata and B. juncea* have tetraploid sets of chromosomes. Because of the close relationship between species within the Brassica genus, it is possible to cross these species and use the crosses for specific breeding. The occurrence of similar plant forms in different Brassica species has resulted in a large number of common names even for the same species which frequently leads to confusion (see Table 1). The English commercial name rapeseed or oilseed rape includes seeds of oilseed turnip rape (*B. campestris* synonymous with *B.* rapa), oilseed swede rape (*B. napus*) and mustards (*B. juncea, B. nigra, B. hirta* synonymous *with Sinapis alba*).

Table 1. Botanical and common names of types of oilseed rape (adapted from Holmes, 1980 and Bailey and Soper, 1985).

Botanical	English	Canadian	French	German
Brassica napus L. Ssp. *Oleifera*				
Forma biennis	Winter rape, oil rape, swede rape, cole		Colza d'hiver	Winterraps
Forma annua	Summer rape, spring rape, oil rape, rapeseed	Argentine Rape Canola*	Colza de printemps Colza d'été	Sommerraps
Brassica campestris L. *(=Brassica rapa)* Ssp. *Oleifera*				
Forma biennis	Winter turnip rape: rape-seed, oil turnip,		Colza, navette d'hiver	Winterrübsen
Forma annua	Summer turnip rape, spring turnip rape	Polish rape, Canola*	Navette d'été, navette de printemps	Sommerrübsen
Var. Chinensis	Chinese mustard		Moutarde chinoise, Pak-choi,	Chinasenf
Var. Pekinesis	Celery cabbage; Chinese kole		Chou chinois, Pet-sai	Chinakohl
Var. Dichotoma	Toria		Toria	Toria
Var. Trilocularis	Sarson		Sarson	Sarson
Brassica juncea L.	Brown mustard, leaf Mustard, Indian mustard, Oriental mustard, rai, raya	Brown mustard, oriental mustard	Moutarde brune	Brauner Senf
Sinapis alba L. *(=Brassica hirta)*	White mustard, yellow mustard	Yellow mustard	Moutarde blanche	Weißer Senf

* Cultivars low in erucic acid and glucosinolates.

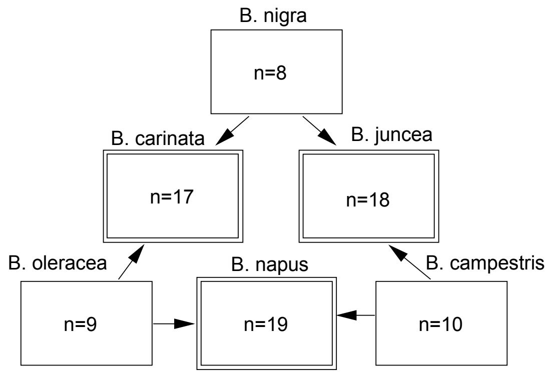

Fig. 6. Specific relationships between rape and related species, basic diploid species are at the corners and the derived allotetraploid species on the sides of the triangle (Holmes, 1980).

Whereas in Europe and the United States the winter form of Brassica napus (rape) predominates, in Canada it is mainly the spring forms of Brassica napus and Brassica campestris that are grown because of the insufficient resistance of the winter types to the very low temperatures of the Canadian winter. Oilseed rape on the Indian subcontinent is mostly cultivated as Brassica juncea (mustard) and Brassica campestris where it is grown as different tree types called toria, yellow and brown sarson. In China, Brassica campestris and Brassica juncea are often replaced by special varieties of Brassica napus.

In nearly all species, the seeds are more or less spherical with a diameter between 1.2-2.8 mm and a weight of 1.5-7 mg. The color of the seeds is mostly black, but sometimes red-brown or yellow (Table 2).

Table 2. Diameter, color and thousand grain-weight (tgw) of the seeds of different rape species (Wagner *et al*., 1999).

	diameter mm	color	g tgw
B. napus	1.8 – 2.8	black-brown	3 - 7
B. campestris	1.2 – 2.5	red-brown-black	1.5 – 3.5
B. juncea	1.4 – 1.8	dark red-brown	1.8 – 4.3
S. alba	2 – 2.8	light yellow-yellow	6 – 10.7

Although all these species are related, they have somewhat divergent morphological and compositional characteristics. In common they contain glucosinolates in all parts of the plant, which limits the use of rape for human and animal nutrition. During the sixties and seventies to improve possible use, breeders developed so called double-low- (or 00-) varieties low in both glucosinolates and erucic acid. In Canada, this type of oilseed rape is called 'canola'.

Brassica napus is self-compatible although both wind and insect pollination can occur. Large amounts of pollen are released and this is likely to contribute to both cross- and self-pollination (Harding and Harris, 1997).

3. The use of oilseed rape

Oilseed rape is a crop with very diverse uses (Fig. 7) and today rape oil is coveted as never before. The reason for this lies in the widespread utilization of rape oil in a variety of sectors including human nutrition, as an alternative regenerative fuel, as an environmental friendly lubricating oil used for very different purposes or as raw material in the chemical industry. Furthermore, the residues from oil production are used as a valuable animal food providing a high energy and a high protein content.

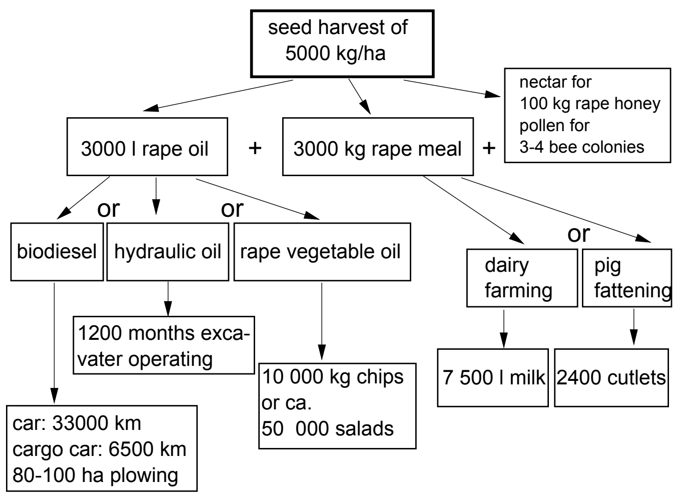

Fig. 7. Examples for possible uses of oilseed rape from a yield of 5 t/ha (UFOP, 2001).

Until the last century the processing of oil crops was carried out locally on a relatively small scale. With industrial development and the invention of steam engines and hydraulic presses, however, seed processing and oil production moved more and more to highly specialized industrial enterprises. The main oil production processes are a combination of pressing and extraction (Fig. 8). After cleaning and crushing, the rapeseeds are slightly heated and then pressed. The resulting residue (cake) still maintains an oil content of 15-18%. This remaining oil can be extracted by a further processing step using a solvent. To provide oil ready for the consumer the press-oil and extracted oil have to be cleaned using several different refining steps. Rape cake and also rape meal which is produced after toasting, drying, and cooking are used as a protein supplements in animal nutrition.

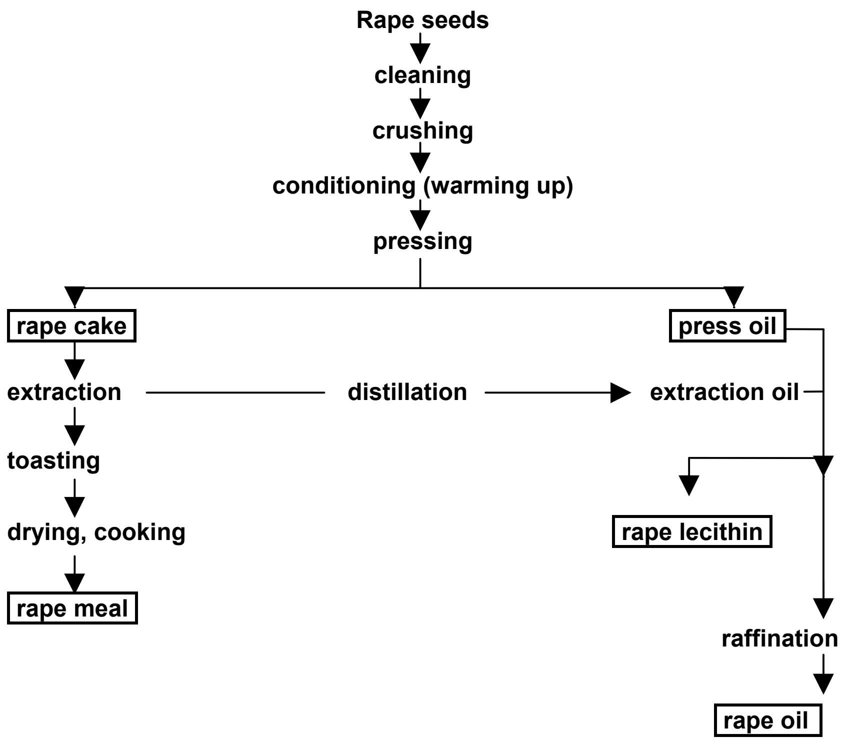

Fig. 8. Basic steps in the processing of oilseed rape.

3.1. Oilseed rape oil in human nutrition

In human nutrition plant lipids and seed oils are preferable to animal fats because of their lower contents of cholesterol and their generally high proportions of unsaturated fatty acids of which linoleic acid and linolenic acid are most important (Beringer, 1977). Both these fatty acids are of vital importance in mammalian nutrition, but since mammalian metabolism does not allow the build up the double bonds which these fatty acids contain they must be supplied as fatty acids in the food.

Formerly the use of rape oil was not considered favorably as a constituent of the human diet because of its unpleasant taste as a consequence of its high content of erucic acid (C 22 : 1). Successful breeding programs over the last 25 years, however, have decreased the content of erucic acid in the rape oil from 40% to almost 0%. Over the same period the percentages of the polyunsaturated fatty acids linoleic acid and linolenic acid of the total fatty acids has increased from 15% to 20% and from 8% to 12%, respectively (Trautwein and Erbersdobler, 1997). The rape oil of today is thus a valuable plant oil for human nutrition with an exquisite flavor. Comparisons of margarines produced from oilseed rape oil and sunflower oil have shown no difference in flavor. In some cases oilseed rape oil has been shown to be superior to other dietary oils for frying and cooking (Gustafson *et al*., 1993). In the USA and Canada, rape oil (or the so-called canola oil) has become the most used of vegetable oils. In comparison with other plant fats and oils the valuable composition of rape oil has many advantages.

Its high content of unsaturated fatty acids mainly oil acid (58-60%) and linoleic and linolenic acid (30-36%) is combined with a very low proportion of saturated fatty acids. Only olive oil and a special sunflower oil from newly bred varieties contain more oil acid. Other plant oils high in the essential fatty acids, linolenic and linoleic acid often contain unwanted saturated fatty acids (Fig. 9). Beside the advantageous composition of fatty acids of oilseed rape oil, the adequate concentration of vitamin E and other plant sterols makes this oil type of valuable quality for human nutrition.

Rape oil is used not only as a highly nutritious cooking oil but also as an important source for the production of other foodstuffs (such as margarine, salad dressings, mayonnaise, baby food) and frying fat for cooking.

In many industrial countries recommendations for the intake of dietary fat focus on decreasing total fat consumption and modifying fat composition. Reducing the intake of products high in saturated fatty acids (such as dairy products, animal fats, meats) is especially recommended in favor of fats and oils containing a high proportion of unsaturated fatty acids. The oil from oilseed rape can be a good source for such oils and it furthermore has the advantage of a valuably high content of the essential polyunsaturated linoleic and linolenic acids (Trautwein, 1997).

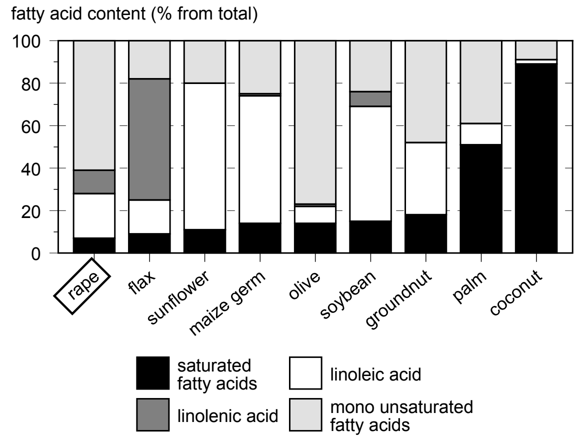

Fig. 9. Fatty acids composition of important vegetable fats (Trautwein and Erbersdobler, 1997).

Polyunsaturated fatty acids, however, are rather sensitive to oxidative degradation and have a low thermal stability. Such oils with a high content of polyunsaturated fatty acids are thus at a certain disadvantage concerning the long-term stability of the fat used for frying, cooking and baking purposes especially in the commercial sector. There have therefore been attempts to breed new varieties with a lower content of polyunsaturated fatty acids in favour of mono unsaturated fatty acids.

New rape varieties have already been bred which have specific fatty acid compositions which comply with the demands of the food industry. From the nutritional point of view, however, it is recommended that only oilseed rape oil with its current fatty acid composition should be used as a dietary oil (Trautwein and Erbersdobler, 1997).

Special peculiarities of oilseed rape oil (after Trautwein, 1997)

- In comparison to other vegetable oils it has the lowest content of saturated fatty acids with only 6-8% of the total fatty acids
- High proportion of the mono unsaturated oil acid with 58-60% of the total fatty acids
- Sufficient content of linoleic acid (20-26% of the total fatty acids)
- Rich in linolenic acid (10% of total fatty acids)
- Favourable proportion of linoleic acid to linolenic acid (2.5:1)
- Rich in plant sterols
- Adequate content of vitamin E

3.2. Rape in animal nutrition

The high source of energy and crude protein is the decisive factor determining the use of oilseed rape in animal nutrition. The high energy source results from the high content of fat made up with a high proportion of unsaturated fatty acids. Rapeseeds cannot be used directly in the nutrition of poultry without costly processing and the use as pig food is limited because of the presence of a high proportion of unsaturated fatty acids (Grünewald *et al*., 1996). For ruminants too a high fat uptake can be detrimental and here too the use of rapeseed is limited (Rohr *et al*., 1978). For this reason and also because of the relative high price of the seeds, the use of residues from the rape oil production rather than rapeseed itself is more common in animal nutrition.

Residues from rapeseed processing can be used as a high value animal food. Besides being high in energy, the residues from rape oil production are also high in crude protein a most important constituent in terms of animal nutrition. The term rape meal describes the residue after the extraction of oil from the rapeseeds (s. Fig. 8). Its high content of crude protein in relation to its market price makes rape meal a popular and widespread protein supplement in animal feed. In the past the part played by rape meal in animal food rations was limited because of "unwanted" substances especially erucic acid and glucosinolates. Both depress food intake by making it much less palatable.

The deciding factor which has brought about the success of the widespread use of rape meal in animal nutrition as seen today has been the development of new varieties with very low contents of erucic acid and glucosinolates (double low or 00-varieties). It has thus been possible to produce rape meal with a content of glucosinolates not higher than 20 mmol/kg seed or 35 mmol/kg extracted meal.

Soybean meal and rape meal in principle shows a similar composition (DLG-Futterwerttabelle, 1997) but rape meal in comparison with soybean meal is lower in protein and higher in crude fibre (Table 3). This is dependent on the relatively high contribution of the fibre containing hulls of the rapeseed.

Table 3. Composition of soybean and rape meal.

	rape meal	soybean meal
	g/kg of dry matter	
Organic matter	923	933
Crude protein	399	510
Crude fat	25	15
Crude fibre	131	67
Ash	77	67

(DLG-Futterwerttabelle, 1997).

The protein composition of rape meal is favorable for animal nutrition. The amino acid composition of the protein decisively determines the quality of the protein. The essential amino acid content of rape meal is of generally good nutritional quality. The higher contents of methionine, cystine, and threonine in comparison to soybean meal are important (Fig. 10). On the other hand, the content of lysine is lower and this must be taken into account if soybean meal is replaced by rape meal (Bell, 1990). Nevertheless, rape meal can compensate for the low lysine content of other animal foods such as cereals and milling by-products. Where sulphur containing amino acids (methionine and cystine) or threonine are limiting acids in rations rape meal can improve the quality of diets.

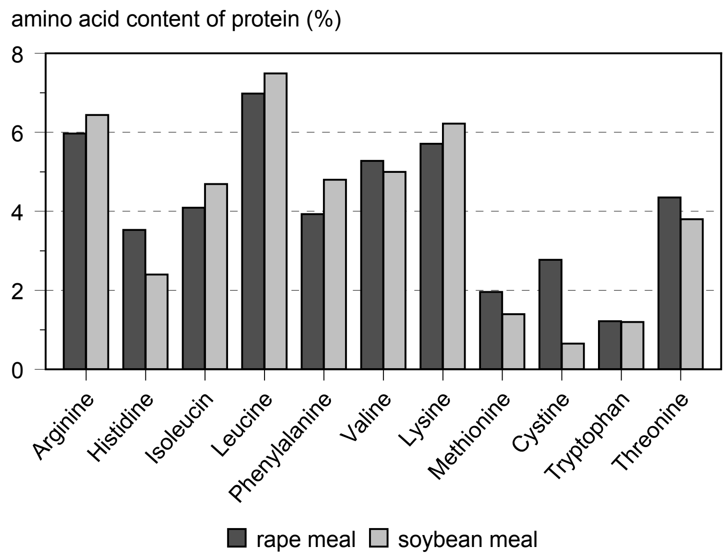

Fig. 10. Essential amino acid content of the protein in rape and soybean meal (Bell, 1990).

The content of ash and minerals, in rape meal generally exceeds that of soybean meal (Lebzien, 1991) (Table 4). P-, Ca-, Mg- and Mn-concentrations are especially much higher than in soybean meal. However, more than half the phosphate is bound as phytate and thus is only poorly available. A major advantage is the very high content of selenium, which is about 10 times higher than in soybean meal. Rape meal is thus a good source of selenium for animals.

Table 4. Mineral content of rape meal and soybean meal (Lebzien, 1991).

	rape meal	soybean meal
macronutrients	g/kg of dry matter	
Ca	7.1	3.2
P	12.3	7.0
Mg	6.2	3.0
K	14.5	21.9
S	5.4	4.8
micronutrients	mg/kg of dry matter	
Fe	230	160
Cu	11	19
Mn	62	33
Zn	75	70
Se	1	0.1

Rape meal in food rations of dairy cows have been tested in many feeding trials with meal from 00-varieties replacing soybean meal to up to 40% of the concentrated feed without disadvantage to food uptake or milk production. In some cases, rape meals up to 3 kg per animal per day produced better results in terms of milk productivity and quality. Rape meal can be used both as a concentrate supplementing protein in a low protein feed such as maize-silage or pressed sugar beet pulps or as a special protein food for high milk performance.

Typical results were published from Sanchez and Claypol (1983) where the supplementation of canola meal was compared with soybean and cotton meal (Table 5). The findings show the beneficial performance in comparison to the other meals.

Table 5. Responses of lactating cows fed rations supplemented with soybean, cotton seed or canola meal (Sanchez and Claypol, 1983).

Response measured	soybean meal	cotton seed meal	canola meal
Milk (kg/day)	34.45	36.50	37.67
Fat-corrected milk (kg/day)	28.07	29.71	32.13
Milk protein (%)	2.95	3.02	2.96
Milk total solids (%)	12.02	12.06	12.01
Flavor quality	7.96	8.09	7.74
Body weight change (kg/day)	0.49	0.36	0.38

A low content of glucosinolates is a prerequisite. Meal from simple 0-varieties (glucosinolates-rich) should not exceed 15-25% in the concentrate or 1.5 kg per animal per day. Feeding concentrate should be especially avoided when it is wet for under these conditions glucosinolates are split up into mustard oils which have an unpleasant taste and flavor and reduce the food intake.

Rape meal can be a good source of protein and amino acids supply in pig feeding because of its favorable amino acid composition. However, a low content of glucosinolates is again a prerequisite. The high content of glucosinolates in rape oil limit the possible extent to which it can be used in pig rations. The detrimental influences of these antinutrional factors on feed intake and on thyroid gland increase with increasing amounts in the diet. Rape meal from 00-varieties can replace half of the necessary crude protein supplement (Table 6). In a feeding experiment with growing pigs the daily gain was only reduced significantly in the last mast period if the rape meal was completely replaced by soybean meal (Burgstaller and Lang, 1989).

Table 6. Response of growing pigs expressed as daily live weight gain in relation to different proportions of rape meal in the protein concentrate feed (Burgstaller and Lang, 1989).

	Mast period < 55 kg live weight			Mast period > 55 kg live weight		
Protein food	Only soybean meal	Half soybean /half rape meal	Only rape meal	Only soybean meal	Half soybean /half rape meal	Only rape meal
Daily gain (g)	670	663	654	804	797	730

These workers recommend the use of not more than 15% rape meal from 00-varieties in the total ration during the last mast period. With this proportion there is no danger of any detrimental influence on meat quality. Similar results have been obtained in other experiments (McKinnon and Bowland, 1977).

Compared with soybean meal, the lower protein and lysine contents have to be taken into account. Studies from Canada showed a response to supplemental lysine (Bell and Keith, 1988), which may depend on the protein level of the basal grain in the diet. An addition of lysine to the canola meal improved feed intake, feed efficiency and daily gain in weight of the pigs (Table 7).

Table 7. Growth and feed utilization response of pigs fed barley-wheat rations from 23-34 kg live weight (Bell and Keith, 1988).

Treatment	daily gain (g)	feed/gain	feed/day (kg)
Protein supplement:			
Soybean meal	624	2.51	1.57
Canola meal	572	2.69	1.53
Canola meal + lysine	602	2.44	1.46

Rape meal is a competitive protein supplement in animal feeding rations because of its high protein content of good quality together with a high content of minerals and vitamins and it is a reasonably priced food in animal nutrition.

3.3. Rape oil for industrial purposes

In the last 10 years, rape oil has been discovered as a raw material able to be used for diverse purposes outside the nutritional sector. A wide range of direct and indirect possible uses of rape oil has been developed. Two main directions of development have occurred: use of rape oil as a source for regenerative energy ('bio-energy') and the direct use of the oil for technical purposes relating to its environmental friendly behavior and special chemical composition (Table 8).

Table 8. Rape oil for industrial purposes.

Predominant use in environmentally sensitive areas	Raw material for the production of various chemicals
Fuel 'Bio-diesel'	Glycerine
Hydraulic oils	Fatty acids
Lubricating fats and oils	(Bio-) Ethanol
Motor oils (2 stroke)	Amines
Offshore drilling operations	Esters
Chain saw oils	Soaps
Metal drilling oils	Paints
Oils for railway points	Varnishes
Framework mould oils	Lacquers
	Softening agents

The use of the oil is without possible negative consequences on the environment for as an energy carrier from the biomass, the CO_2-cycle is closed because the carbon dioxide released during combustion is refixed in the production of new plant material and thus does not leak into the atmosphere.

Pure rape oil can be employed as fuel only in special motors which unfortunately are not in widespread use. For diesel engines rape oil is processed with the addition of methanol to produce the so-called 'bio-diesel'. Using this fuel it is possible to replace diesel from mineral oil totally without necessary modification of the motor. 'Bio-diesel' can be rapidly decomposed biologically in soils and water. In environmentally sensitive areas 'Bio-diesel' should especially be used, as for example for all vehicles in water and nature reserves.
In several experiments in Europe and the USA it has been shown that a motor with 'Bio-diesel' does not produce a greater amount of exhaust than with diesel from mineral oil and in fact most of the exhaust values are lower (Table 9). 'Bio-diesel' is virtual free of sulphur. For this reason the exhaust fumes are also free of sulphur oxides so that there is no leakage of these oxides into the atmosphere to cause acid rain.

Table 9. Exhaust of a diesel motor powered with 'Bio-diesel' in comparison to diesel from mineral oil (Scharmer and Golbs, 1997).

	'Bio-diesel' in comparison to diesel without	with catalyst
Carbon monoxide CO	5 -10% lower	60 - 90% lower
Hydrocarbon HC	25 - 40% lower	70 - 90% lower
Particles	9 - 50% lower	60 - 90% lower
Nitrogen oxides NO_x	Motor specific 0 - 8% higher	2 - 5% higher

For this reason especially in some highly populated industrial countries, consumption of 'Bio-diesel' has increased considerably in recent years. For example in Germany the use of 'Bio-diesel' has risen from 0 to an estimated 400 000 t/year over the last 10 years (Fig. 11).

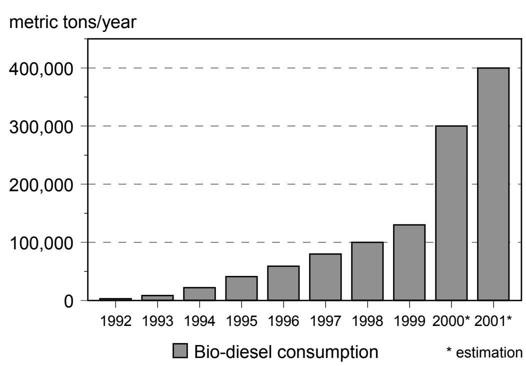

Fig. 11. 'Bio-diesel' consumption in Germany 1991-2001 (Bockey, 1998; UFOP, 2001).

The fast biological decomposition of vegetable oil in soils and water is a great advantage in comparison to mineral oils. Vegetatively based hydraulic oils and lubricants are also characterized by very rapid biological decomposition. In only 5 days, they are almost totally decomposed, a rate which exceeds the legal requirements for biological decomposition. With the legal test (method CEC-L 33-T 82) 80% of the oil must be biological decomposed within 21 days. However, for mineral oils only 15-20% is decomposed in this time (Fig. 12). For this reason hydraulic and lubricating oils based on rape oil are classified as 'not endangering for water' whereas mineral oil is classified as 'dangerous for water'.

Because of its rapid rate of decomposition, rape oil is being used directly and widely in many sectors (Fig. 12) with very different consumers using oils with a rape oil base. Communities for example use rape oils in various forms of machinery, for caterpillars on disposal sites, excavators, motor-saws and lawn-mowers. For shipping and water supply in agriculture and the building industry, the favorable environmental behavior of vegetable oil is of special importance. Rapeseed oil is as efficient as mineral oil for use as a base fluid in the muds to flush away debris during offshore drilling operations with great environmental benefit because of its lower toxicity.

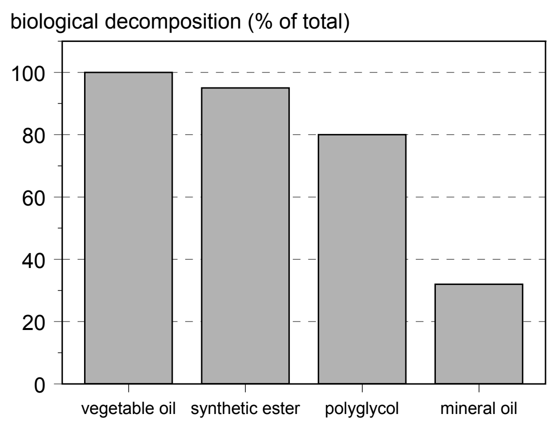

Fig. 12. Biological decomposition of different base oils within 21 days (UFOP).

In the chemical industry rape oil is a raw material for producing special chemicals such as glycerin, amines, esters, soaps, paints, vanishes, lacquers. New research findings indicate that in future it will be possible to use the oil as a softening agent in the production of PVC-materials. In other research projects there have been attempts to convert rape oil to polyol-components for the production of the often used polyurethane.

4. The role of plant nutrients in yield physiology and deficiency symptoms

Thirteen mineral nutrients are essential for oilseed rape as is the case for all other green higher plants. In the literature, several classification systems have been proposed. The following (Table 10) based on the work of different authors and considers the physiological and biochemical properties of the nutrients (Mengel and Kirkby, 2001). All these elements are equally essential and cannot be replaced by another nutrient although the absorbed quantity and the required demand varies considerably between the nutrients. With a complete lack or an insufficient supply of only one nutrient, normal plant growth can not take place.
It is not possible to describe in detail the functions of each of the nutrients in plant physiology in this booklet. Nevertheless a short summary should be given with special references to the oilseed rape crop.

4.1. Nitrogen

Nitrogen is an integral component of amino and nucleic acids, proteins, nucleotides, chlorophyll, chromosomes, genes, ribosomes and also a constituent of all enzymes. This wide range of different N-containing plant compounds explains the important role of nitrogen for plant growth. Nitrogen deficiency in an early stage of development inhibits vegetative growth, reduces productivity through lower leaf area index and shortens the period of photosynthetic activity (Fig. 13).

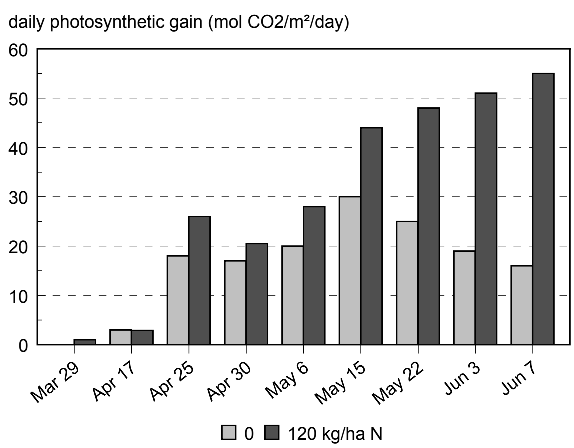

Fig. 13. Daily photosynthetic CO_2 gain of oilseed rape affected by two different rates of N fertilization (Kappen *et al*., 1998).

Table 10. Classification of the plant nutrients according to their physiological and biochemical properties (according to Mengel and Kirkby, 2001).

Functional group	nutrient elements macro- micro nutrient	uptake as	physiological and biochemical properties
I	C H O N S	CO_2, HCO_3^-, H_2O H_2O, O_2, NO_3^-, NH_4^+, N_2, SO_4^{2-}, SO_2 The ions from the soil solution or via leaves; the gases from the atmosphere	Main constituents of organic matter, essential elements of atomic groups involved in enzymatic processes. Assimilation in the organic matter by oxidation-reduction processes
II	P (Si) B	phosphate, silicate, boric acid or borate from the soil solution and via leaves	Esterfication of the phosphate, silicate and borate ions with native alcohol groups in plants. The important phospate esters are involved in energy transfer reactions
III	K Ca Mg (Na) Cl Mn ↓	ions from the soil solution or via the leaves	Non-specific functions in establishing the osmotic potential of plant cells. More specific reactions in which the ion activates enzyme reactions about optimum confor-mation of enzyme proteins. Bridging of the reaction partners (enzyme-substrate). Controlling membrane permeability and electron potential; balancing indiffusible and diffusible anions
IV	Fe Cu Zn Mo	ions (Mo as MoO_4^{2-}) or chelates from the soil solution or via the leaves	Predominantly present in a chelated form incorporated in prosthetic groups of enzymes. Enable electron transport by valency change

Development of an adequate number of pods is therefore limited. Later the assimilation of these pods contributes to a great part to seed growth (Kullmann and Geisler, 1988). Restricted N-nutrition reduces the number of seeds per plant and seed weight of oilseed rape regardless of variety (Table 11). Very similar results were obtained in Indian field experiments with raya (*Brassica juncea*) where increasing N rates from 100 to 150 kg/ha N increased the number of branches/plant, the number of pods/plant, the number of seeds /pod and the seed weight (Singh *et al*., 1997a).

Table 11. Effect of N-nutrition on yield components of oilseed rape (Forster, 1977).

	Weight per seed in mg		Number of seeds per plant (in 1000)	
	N_1	N_2	N_1	N_2
0-variety	4.3	4.9	1.5	3.1
00-variety	3.8	4.3	2.0	3.7

N-deficiency not only limits yield but also the protein content of the seeds. The marked competition for assimilates between different metabolic sinks has to be considered. Increasing protein content decreases oil content (Forster, 1977). In a pot experiment with oilseed rape, it was shown that regardless of variety, the higher N-treatment led to a higher protein content but to a lower oil content. Nevertheless, the oil yield per pot was higher at the N_2-level (Fig. 14). It is thus obvious that N nutrition must be optimized to compromise between seed yield and seed quality.

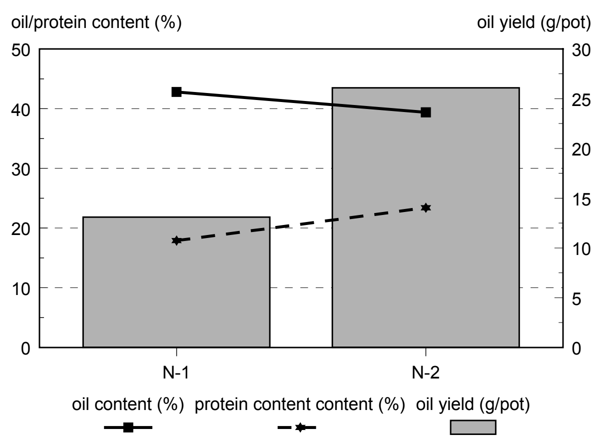

Fig. 14. Effect of N nutrition on the oil and protein content and the oil yield of 00-varieties of oilseed rape (Forster, 1977).

Furthermore nitrogen exercises a certain control in phytohormone regulation within plants. N-deficiency accelerates the production of abscisic acid which plays a role in the aging processes and so shortens the growth period and the filling of assimilates in the seeds. Thus, nitrogen is not only a constituent of many different compounds in the plant but also has an effect as a regulating nutrient in the phytohormone balance.

Nitrogen deficiency symptoms

Because of the great importance of nitrogen for the development of the whole plant, N-deficiency leads very rapidly to reduced and retarded growth and lower yields. The deficiency-symptoms are rather well known and can be corrected relatively quickly and easily by fertilization. The length, width and area of leaf blades decrease under N-deficiency. Although the stems are thinner than in plants well supplied with N the resistance to lodging remains greater. In leaves the color changes to pale green in the younger leaves and yellowish green in the older ones. Nitrogen is mobile within the plant and is retranslocated from the older to the younger plant parts. Thus, symptoms appear first in the older leaves whereas the younger parts remain green for a certain time. This fact can be used to distinguish between N- and S-deficiency: In contrast to nitrogen, sulphur cannot be retranslocated, so that S-deficiency always begins in the younger leaves.

In some cases, rape plants lacking in N show a discoloration of the older leaves to reddish and reddish-violet similar to P-, Mg- or S-deficiency. But in the case of N shortage the reddish color is always accompanied by a pale or yellow green color of the whole plant, tissue necrosis and enhanced senescence of older leaves. Tillering is poor and only few branches are established. The rape canopy in the field remains thin and open. In later development stages flowering is reduced, flowering and ripening periods are shortened, and pod numbers are low. Seed yields are strongly depressed.

4.2. Sulphur

Sulphur plays an indispensable role in rape plant metabolism as a component of proteins and glucosinolates. It is taken up by the roots as sulphate and transported via the xylem to the leaves where it is reduced to cysteine and either converted to methionine or incorporated into proteins and cysteine containing peptides such as glutathione. Hence, sulphur is essential for protein formation, important for a high protein content in rapeseeds.

Not only the amount of protein but also the quality of protein is influenced by the S-status of plants. Under conditions of sulphur shortage plants produce lesser amounts of S-containing amino acids and thus the composition of protein is also influenced, lower proportions of methionine and cysteine being present (Wrigley *et al*., 1980 in Marschner, 1995). Thus, under conditions of sulphur deficiency, protein synthesis is inhibited.

In green leaves most of the protein is located in the chloroplasts. Hence it is not surprising that under insufficient S-supply the chlorophyll content declines (Bergmann, 1992) and the green color of leaves becomes lighter and changes to yellow because of chloroplast damage and decreasing chlorophyll content. As soon as 3 - 7 days following sulphur fertilization the color of rape leaves changes once more back to the normal dark green if the duration of S-deficiency has not been too long.

The S containing amino acids are also precursors of other compounds such as coenzymes and secondary plant products. For example glucosinolates are typical secondary S-containing plant products of Brassica species affecting plant resistance to pests and diseases. Glucosinolates are preformed resistance barriers to the plant which contribute to a general plant defense mechanism (Schlösser, 1983). On the other hand a high content of glucosinolates impairs the quality of oil and meal. Because of the increasing effect of excessive S-nutrition on the glucosinolate content (Table 12) sulphur fertilization must be optimized to obtain high yields of good quality. Low S supply impairs the quality of rapeseeds because the oil content decreases.

Table 12. Effect of sulphur supply on yield and mustard oil content of the shoots of *Brassica juncea* (Marschner, 1995).

Sulphate supply (mg S/pot)	Shoots (g fresh wt)	Mustard oil content (mg/100 g fresh wt)
1.5	80	2.8
15.0	208	8.1
45.0	285	30.7
405.0	261	53.1
1215.0	275	52.1

Based on Marquard *et al*. (1968).

Because of the central role of sulphur and nitrogen in the production of proteins there is a close relationship between the supplies of S and N in plants. For many different crops and also for oilseed rape, it has been shown that high rates of nitrogen create sulphur deficiency if the sulphur nutrition is not adequate to meet the higher N supply (Blake-Kalff *et al*., 1998). On the other hand, the efficiency of nitrogen fertilization is improved through an adequate supply of sulphur (s. chapter 6.2.1).

Sulphur deficiency symptoms

Not only in the Northern Hemisphere but also elsewhere, visible sulphur deficiency symptoms are widespread owing to declining atmospheric depositions over the past 10-20 years together with an increasing use of non S-containing fertilizers. A high input of nitrogen fertilizers induces a more intensive appearance of a sulphur shortage. Also the development of new 00-varieties of *Brassica napus* low in erucic acid and in glucosinolates has been associated with an increase in cultivation of this high demanding S crop with the potential risk of S deficiency. Deficiency symptoms have been described in detail by Schnug and Haneklaus (1994a) and Feger (1995).

In winter rape varieties, deficiency symptoms have been observed as early as in autumn, first in the younger leaves where the color changes to light green and yellow with the chlorosis beginning from the outer parts of the leaf but the tissue around the veins remaining green. In contrast to severe N-and Mg-deficiency, necrosis is absent under S-deficiency. The first symptoms appear in areas within a field where the development of the root system is disturbed by poor soil structure or restriction to drainage in the soil profile. Plant growth is reduced at a very early stage. During stem elongation the main period of S-uptake, the leaves remain smaller. The whole plant shows a rigid, erect appearance. Under severe S-shortage the youngest leaves particularly show a spoon-like deformation, often together with a reddish discoloration because of an enrichment of anthocyanins. Under Mg- and Mn-deficiency leaf chlorosis also occurs but in the presence of dark green veins, the spoon-like deformation of leaves, however, is typical for a lack of S.

The onset of flowering is delayed and the color of the petals changes from bright yellow to pale yellow and under severe S-deficiency conditions to white petals. Additionally the petals are smaller. The flowering period is particularly critical for yield formation because the fertility of flowers is reduced under S-deficiency. Even at this late stage of development it is possible to correct S-status by foliar fertilization and it is highly effective. With S deficiency the whole flowering period is prolonged in comparison to well supplied plants, so it seems that in fields that are insufficiently supplied the flowering period is not completed even though the first plants are already mature and the pods have burst.

The number and size of pods is reduced. During pod development the number of seeds per pod decreases. With severe deficiency the pods remain almost empty. Only one or two seeds per pod are established, in order to form few but intact seeds for regeneration.

S-deficiency symptoms are frequently observed on light soils, poor in organic matter, or on soils with a poor soil structure and especially under conditions with high precipitation, leading to considerable S-leaching. Because of the increasing use of highly concentrated NPK-fertilizers containing no S and the decreasing S-deposition from the air and rain it would seem that in future S-deficiency symptoms are likely to be present on greater areas of land at present unaffected.

4.3. Phosphorus

Phosphorus is a constituent of several essential cell components like nucleotides, nucleic acids, and phospholipids. The last named are essential for different cell membranes to maintain the cell structure. P promotes root development, early flowering and ripening. It is particularly important in early growth stages. Phosphorus plays an indispensible role within the energy storage and transfer in the form of AMP, ADT, ATP, NADP or NADPH. So it is obvious that rape needs a high P-supply to build up a high content of high energy containing oil. On the other hand oilseed rape shows a high efficiency in the P-uptake because of a high influx-rate through the root hairs (Föhse and Claasen, 1991). P-deficiency in rape restricts both top and root growth. High rates of phosphorus increase the oil and protein content (Bailey and Grant, 1990) and can lead to earlier maturity of rape plants, which is of special importance in short-season areas (Ukrainetz *et al*., 1975).

Phosphorus deficiency symptoms

Rape plants suffering from phosphorus deficiency show both retarded top and root growth. Stems are thin, the plants are erect with few branches and small, narrow leaves. Since phosphorus is mobile within the plant, deficiency symptoms appear first in the older parts with a dull reddish, reddish violet to deep purple discoloration of stems and leaves because of enhanced formation of anthocyanins. Particularly in early stages of development P-deficient plants may become a darker blue green due to a preferential formation of the darker chlorophyll in the younger leaves. Older leaves are a bright red or orange and fall prematurely.

4.4. Potassium

Unlike many other essential nutrients potassium is not incorporated into organic matter and does not become part of the chemical structure of plants but is present in unbound form in the cytoplasm where K is highly mobile. The range of its physiological functions is very wide. Potassium is involved in the activation of a large number of enzymes and hence controls many physiological functions, for example, formation of proteins and chlorophyll, carbohydrate metabolism (respiration) and regulation of transpiration and water use efficiency as well as in the production and translocation of assimilates to the storage organs. K provides strength to plant cell walls and is involved in the lignification of sclerenchyma tissues. By improving carbohydrate synthesis K promotes oil synthesis, where carbohydrates are required as essential components.

Potassium functions in the active transport of assimilates through the plasma membrane into the phloem and in passive flow of photosynthates in the sieve tubes. Adequate K nutrition ensures the adequate translocation of assimilates to the seeds (Haeder, 1977). The high K concentration in young tissues is necessary for effective enzyme activation. It is the preferred cation to maintain cell turgor and hence, plants with insufficient K supply have a low water use efficiency as reported for cereals (Grzebisz, 1998) as well as for oil crops (Lindhauer, 1985). This is of importance for areas with low precipitation or drought periods during vegetation.

K increases leaf area and leaf chlorophyll content, delays leaf senescence and therefore contributes to a greater canopy photosynthesis and crop growth.

Potassium is known to improve resistance to a number of pests, diseases and environmental stresses caused by temperature, moisture, transpiration, wind, saline conditions, etc. The positive effect of K on frost resistance is reported in several publications (i.e. Marschner, 1995; Mengel, 1991; Bergmann, 1992) which may be important in cultivation areas with hard winters or in areas which frequently suffer from late frost periods in spring.

K deficiency can be one reason for early lodging because of a reduced growth rate of the cambium in stems of rape (Pissarek, 1973). The early lodging and the restricted formation of xylem and phloem limit the translocation of nutrients and assimilates to the upper plant parts and into the seeds.

In less specific processes potassium can be replaced by sodium. But this substitution depends on the uptake potential of Na of the crop which is, however, low for rape (Marschner, 1971). A fertilizer trial with sodium showed no yield response. Only under very severe K deficiency may a certain beneficial influence on yield formation be supposed (Pissarek, 1981). Thus, for the oilseed rape crop only very small amount of K can be replaced by sodium and this is probably one reason for the high K demand of rape crops.

Potassium plays an important role in the activation of enzymes of assimilate metabolism and their conversion to oil. Some authors report that the influence of potassium on the oil content of the seeds is only small (summarized in Holmes, 1980). However, this probably depends on variety and yield. The new varieties give higher yields but this yield potential can only be achieved if the higher nutrient demand is met. It has thus been observed that potassium has a beneficial effect on the oil content of new varieties high in yield but only has a small effect on an old variety producing a low yield (Forster, 1977). The influence of potassium on the content of protein or glucosinolates is only low (s. chapter 6.3.4.1).

Potassium deficiency symptoms

In contrast to N- or P-deficiency with a more erect plant habit potassium deficient plants exhibit a characteristic tendency of wilting on hot and sunny days, even if no other symptoms can be seen. Rape plants show decreased drought resistance due to impaired turgor and stomata regulation. With continuous K-deficiency the total growth is retarded with shorter internodes, the leaf blades of younger leaves remain smaller. Since the K^+-ion is very mobile deficiency symptoms become visible first in the older leaves with marginal and interveinal yellowish-brown chlorosis. Under severe deficiency conditions the symptoms develop to necrotic tissue beginning from the leaf margin, and the leaves may die and fall. Margin and leaf scorch are considered to be typical potash deficiency symptoms, similar to water deficiency.

The stem diameters are reduced under K-shortage. The lignification of vascular bundles is impaired (Pissarek, 1973), both leading to increased lodging of rape plants due to a lower cambium activity under K deficiency conditions. Lack of potassium impairs winter hardiness and reduces resistance to plant diseases and infections. Numbers of pods are restricted. Often the successive and younger leaves show a darker bluish-green color in comparison to well supplied plants, similar to the discoloration under P-deficiency. The leaf surface is often undulating and the blades are bent downwards.

4.5. Magnesium

The most well known function of magnesium within green plants is its position in the center of the chlorophyll molecule. For this reason Mg deficiency leads to a rapid breakdown of chlorophyll and also other pigments (Table 13) because of a restricted protein synthesis.

Table 13. Magnesium deficiency-induced changes in plastid pigments and leaf dry matter in rape* (Marschner, 1995).

Treatment	Chlorophyll (*a* and *b*) (mg/g fresh wt)	Carotenoids (mg/g fresh wt)	leaf dry matter (%)
Control	2.33	0.21	13.6
Magnesium-deficient	1.33	0.11	17.7

* Based on Baszynski *et al*. (1980).

Despite this central function a proportion of only 20-30% of total Mg is bound to chlorophyll. Most plant magnesium is in soluble form, associated with different organic and inorganic ions. Mg is required in substantial quantities in other important physiological processes, mainly as an activator or cofactor for many enzyme reactions. It is involved in nearly all processes transferring energy during phosphorylation, maintaining electroneutrality in the cells, and metabolism of carbohydrates. It plays an important role within the synthesis of proteins. Generally in Mg deficient plants the proportion of protein-N is depressed in favor of non protein-N. Often a high content of nitrate can be found in such plants which can be toxic for cattle receiving forage rape. The rate of photosynthesis and respiration is lower than in adequately supplied plants.

Mg deficiency can occur not only as a result of low Mg concentrations in the soil but also by the influence of high concentrations of other cations including K, NH_4, Ca or even Mn and Al in the soil solution, even if such soils show an apparently adequate Mg status according to soil analysis. Fertilization must thus consider the imbalance of nutrient supply influencing yield and quality.

Magnesium deficiency symptoms

Because of the central position within the chlorophyll molecule Mg-deficient plants lack chlorophyll. Typical symptoms are therefore intercostal chlorosis of fully expanded rape-leaves beginning at the older part of the plants. Often the chlorosis starts with marbling and discoloration to pale green, greenish yellow and yellow colors in the form of blotches advancing from the leaf tip and margin towards the midrib. The veins and the neighboring tissue remain dark green. Under acute Mg-shortage conditions the color of intercostal chlorosis even changes to reddish brown and violet, followed by necrosis of the tissue. In the field, Mg deficiency is often discernible in the form of blotched areas growing side by side with areas without visible deficiency symptoms giving the canopy an uneven appearance.

4.6. Calcium

Although calcium is without doubt an essential nutrient, Ca deficiency is rarely observed under field conditions. In most cases even under acidic conditions the Ca-concentration in the soil is sufficiently high for the demand of the plant. Calcium is indispensable within the plant for the stabilization of cell walls and maintenance of membrane integrity. A high proportion of calcium is located in the cell walls. It is involved in the regulation of the cation/anion-balance. In contrast to magnesium, calcium is an activator of only few enzymes, mainly membrane bound enzymes. Although the quality of some vegetable and fruit crops falls with decreasing Ca-content no indications of this have been published concerning rape quality.

Calcium deficiency symptoms

Although the calcium demand for optimum growth is much higher in dicotyledons than in monocotyledons Ca-deficiency symptoms of rape plants are not very often observed. Mostly the lime demand of the soil is higher than the requirement of the plant. Thus, deficiency symptoms have rarely been described. In mustard and rape, plants have been observed with soft stalks in which the inflorescences are bent over due to the weakly developed collenchyma. Chlorotic and necrotic spots appear on the younger leaves.

4.7. Micronutrients

As is already indicated by the name, plant uptake of micronutrients is much lower than that of macronutrients. Nevertheless the importance of these elements has increased in recent years and will increase further (Bergmann, 1992) for the following reasons:

- increasing yields due to high yielding varieties also places a rising demand on available micronutrients;
- increasing use of lime fertilizers to maintain soil fertility and to avoid soil acidification depresses the availability of many micronutrients restricting crop yield and quality;
- increasing use of highly concentrated NPK-fertilizers poor in micronutrients;
- increasing concentration of livestock with agricultural areas separated into 'arable' and 'livestock' regions prevents micronutrient recycling in the form of animal manure in arable areas;
- high inputs of macronutrients may reduce the uptake of micronutrients because the equilibrium of ions in the soil solution is disturbed to the disadvantage of the micronutrients.

The importance of micronutrients for plant physiology lies in their influence on enzyme reactions and therefore deficiencies may severely limit crop yields.

4.7.1. Boron

In comparison to other crops, Brassica species have a relatively high B requirement and react sensitively to B deficiency. Boron plays a key role in cell wall biosynthesis and in regulating membrane permeability, tissue differentiation, carbohydrate and protein metabolism, cell division and cell elongation, pollen germination and pollen tube growth, ensuring adequate seed set in the pods which is important to achieve a high seed yield. Under B deficiency, pollen viability and seed set of rape is greatly reduced (Nyborg and Hoyt, 1970) and protein formation is also restricted.

Boron deficiency symptoms

A lack of boron in contrast to other nutrients is the only deficiency which accelerates physiological processes instead of reducing them. It seems that all boron deficiency symptoms can be attributed to uncontrolled tissue proliferation such as increased cell division in the cambium without cell differentiation (Bussler, 1973) leading to abnormal cell growth and the bursting open of stems. The internodes of stems are stunted and the whole plant appears squat giving a bushy or rosette appearance.

Rape leaves lacking boron are a paler green, in some cases with reddish discoloration and/or interveinal yellow mottling (Nyborg and Hoyt, 1970). The edges of younger leaves are unrolled. With continuing B shortage, new leaves are deformed and stems crack. The whole leaf blade growth is considerably reduced. Leaves at the base of the plant begin to die and at harvest most have already fallen from the plant. The abnormally thickened stems often show brown necrotic, corky lesions and cracks and there is a tendency to rupture. The stems are often hollow. Flowering appears restricted and distorted, the inflorescence is compact and irregular with infertile flowers. Buds and flower drop is typical. The number of pods and particularly seed set are greatly reduced by B deficiency.

4.7.2. Manganese

Oilseed rape is classified as a crop with a medium demand for manganese (Bergmann, 1988). Manganese functions partly as a constituent of some enzymes and partly as an activator of other enzymes. Mn is involved in photosynthetic O_2 evolution, carbohydrate metabolism and lipid synthesis. Mn is required for the formation and stability of chloroplasts, protein synthesis, and nitrate reduction. Mn deficient plants show not only restricted seed yield but also a lower oil content of the seeds and an alteration of the fatty acid composition of the oil. For soybean it has been shown that under Mn deficient conditions the content of oleic acid is decreased whereas the content of linoleic acid is increased (Wilson *et al*., 1982).

Manganese deficiency symptoms

Intercostal chlorosis of middle and younger leaves is the typical symptom of manganese deficiency, beginning at some distance from the veins. These chlorosises in rape plants are generally distributed all over the leaf blade in the form of spots in contrast to S-deficiency where the chlorosis starts at the leaf margins and the tissue along the veins remains green. Leaves of Mn-deficient rape appear spotted and mottled with a greenish-yellow and yellow color. Under continuing deficiency conditions, the tissue of these spots dies and necrotic lesions become visible (Schnug, 1992). The onset of flowering is retarded and pod development is reduced. Ripening and harvest periods are delayed.

In some cases, it is difficult to distinguish between Mg-, Fe- and Mn-deficiency because of the similarity of the symptoms. However, Mg-deficient plants first show symptoms in the older leaves whereas evidence of a lack of Mn appears first on the young and moderately young leaves. This is also true of Fe-deficiency but in this case leaf veins are always sharply delineated.

It is also typical under Mn-deficiency conditions in the field, plants growing on compacted areas, develop much better than in the field as a whole. The same is true of plants growing in the vicinity of the "tram lines" indicating compacted soil resulting from agricultural machinery. This phenomenon can be explained by the effect of oxygen-shortage in these compacted zones increasing plant available Mn^{2+}-cation as a consequence of a lower redox potential in comparison to the neighboring zones of more thoroughly aerated soils. In these more aerobic conditions, Mn is oxidized to the non-available Mn-oxides so that Mn deficiency appears in the plants.

4.7.3. Molybdenum

Molybdenum is a relatively "new" trace element as it only 50 years ago, that it was discovered to be an essential nutrient because of the very low Mo content in plants in comparison to the other micronutrients. Nevertheless, oilseed rape is characterized as a crop with a medium demand for molybdenum (Bergmann, 1988). The functions of Mo are related to the valency changes within the metabolism as a metal component of enzymes. Mo is required in nitrate reducing enzyme systems. Mo deficiency greatly decreases the activity of nitrate reductase. Hence, it is involved in the formation of protein. Deficiency causes nitrate accumulation and impairs N utilization and efficiency.

Molybdenum deficiency symptoms

Deficiency symptoms are often observed in the leguminosae- and crucifereae-families. Although oilseed rape is a Mo-sensitive plant, the total demand is not very high because of the very low Mo-content in the plant. For this reason, Mo deficiency symptoms are rarely observed under field conditions. In contrast to all other trace elements, Mo availability in the soil increases with rising pH and Mo deficiency is thus mainly restricted to acid mineral soils.

Mo deficient rape plants produce a sticky, brown sirupy substance on the leaves and leaf veins (Bussler, 1970). This brown substance, which can also be observed microscopically in cells of the vegetative growing point, is the cause of the development of deficiency symptoms which include: Local chlorosis and necrotic lesions along the main veins of mature younger leaves with smaller leaf blades, a twisting around the central midrib and upward curling of the margins. In cauliflower, it is known as whiptail (Marschner, 1995).

Under extreme Mo shortage only the midrib continues to grow, and the leaf lamina is not formed. Often the development of the vegetative growing point is disturbed by the formation of necrotic lesions and dies. Marginal chlorosis and necrosis appear on older leaves which have a high content of nitrate. Often the leaf margins change their color to gray and white, whereas the blades remain their normal green or gray-green. Branches per plant, pods per plant and seed set and seed weight are decreased when there is a shortage of Mo (Sinha *et al*., 1990).

4.7.4. Copper and zinc

Rape seems to be less sensitive to copper and zinc deficiency than are cereal crops and it is therefore rather unusual for deficiencies of these elements to arise. Mustard for example is classified as a plant which is highly tolerant to Zn deficiency in comparison to maize, soybeans or flax which have a lower tolerance (Viets *et al*., 1954). Nevertheless deficiency may occur, particularly under special soil or cultivation conditions which favor the deficiency such as high soil pH, excessive liming, or a high content of soil organic matter.

Several proteins contain copper especially in the chloroplasts. Under deficiency conditions chlorophyll content and photosynthesis is restricted, which is reflected in lower carbohydrates formation. Insufficient Cu supply limits pollen formation and seed set and leads to poorly filled pods. Cu is a regulatory factor in enzyme reactions and a catalyst of oxidation reactions.

Zinc is a constituent or acts as a cofactor of several enzymes especially within carbohydrate metabolism and protein synthesis. Protein formation is particularly reduced in Zn deficient plants, a factor important for high protein-containing seeds of rape crops.

Zn deficiency is more widespread on soils of high pH and on calcareous substrates. High rates of P fertilizers increase the risk of Zn deficiency on soils with a low or moderate zinc content. High application rates of K and Mg fertilizer improves Zn uptake as do also physiological acid fertilizers (NH_4^+).

Zinc deficiency symptoms

Under field conditions Zn deficiency may appear on acid highly weathered soils with a very low Zn-content, particularly on sandy or loamy sandy soils after high applications of phosphorus or/and liming materials. On neutral or particularly calcareous soils Zn availability decreases and therefore the risk of a lack of Zn arises especially on high pH soils with a high phosphorus content. Mustard is a plant species with a high tolerance to Zn shortage, although differences between varieties may occur. Zn deficiency symptoms are thus not very often described (Viets *et al*., 1954). Generally the most typical symptoms are stunted growth with shortened internodes leading to a bushy habit of the plants, also called "rosetting" or "rosette disease". The leaf-size is drastically reduced, in some cases combined with chlorosis.

Copper deficiency symptoms

The general symptoms of a lack of Cu in plants are distortion, wilting, bleeding and death of younger leaves, necrosis of the apical meristem, retarded development of all organs, shortened internodes and premature development of axillary branching of shoots. The younger leaves of Cu deficient rape are larger than from well-supplied plants (McAndrew *et al*., 1984). Chlorosis of younger leaves has also been observed in which the leaf veins remained green in color (Bergmann, 1992). The whole plant phenotype resembles a plant suffering from water deficiency with permanent wilting and limp leaves. Generative development is also disturbed with a compressed flower inflorescence and poorer formation of flowers.

4.7.5. Iron and chlorine

Although there is no doubt about the essential role of iron and chlorine as nutrients, little information is available about their specific requirements for oilseed rape. Iron is involved in the formation of chlorophyll, N assimilation, nitrate reduction, and protein synthesis. Fe deficiency is more induced by external conditions of the soil (high pH, low O_2 concentration because of soil compaction, high water content, lime and alkaline soils, physiological alkaline fertilizers) than by an absolute low Fe content of the soil.

Iron and chlorine deficiency symptoms

Under normal field conditions it is not possible to induce chlorine deficiency. Chlorine is involved in the regulation of cell osmotic pressure and transpiration and plays an important role in O_2-production in photosynthesis. Since the Cl supply via fertilizers, precipitations and soil content is more than highly adequate, Cl deficiency does not come into question.

Table 14. Short description of the nutrient deficiency symptoms in oilseed rape.

Symptoms mainly on older leaves first				Symptoms mainly on younger leaves first
N	P	K	Mg	S
Decrease of length, width and area of leaf blades; Pale green, yellowish discoloration	dull reddish, reddish violet to deep purple discoloration of leaves and stems	marginal interveinal yellowish-brown chlorosis and necrosis of leaves, wilting of leaves on hot days, increased sensitivity to frost and drought	intercostal chlorosis of leaf blades with remaining green of the veins and neighboring tissue	light green and yellowish discoloration of the leaves, beginning from the margins, veins remain green, spoon like deformation, often together with reddish discoloration
Thinner stems, poor ramification, reduced flowering, low pod set		retarded total growth with shorter internodes, reduced stem diameters	Mg deficiency within a field often with blotchy areas adjacent to areas with unaffected plants	rigid, erect appearance of the whole plant, pale yellow, white petals, prolonged flowering period
Whole field appears poor and yellowish, shortened ripening period	delayed maturity	reduced pod number		reduced number and size of pods, reduced seed set per pod

Table 14. Continued.

Symptoms mainly on younger leaves first						
Ca	Fe	Zn	Cu	B	Mo	Mn
chlorotic and necrotic spots on leaf blades	intercostal chlorosis of leaves		larger leaves with chlorosis at blades, remaining green of veins, retarded growth of all organs	paler green and reddish discoloration of leaves and interveinal yellow mottling, bushy appearance of the plant	local chlorosis, necrotic lesions along the main veins of leaves, sticky brown sirupy substance on the leaves and leaf veins, "whiptail symptom"	intercostal chlorosis of leaves in spot form, deficiency symptoms on
		stunted growth with shortened internodes	plants look like suffering from water deficiency	stunted stem internodes, thickened stems, often hollow with brown necrotic, curly lesions, many unfertile flowers with drop of flowers and buds	Reduced branches per plant	retarded flowering start
			poorer flower formation	reduced number of pods and seeds per pod	reduced pods plant and set per pool	reduced pod development delayed ripening and harvest time

However, on salt affected soils chloride is considered more in the context of toxicity. However, *Brassica napus* is classified as 'moderately tolerant' (Bergmann, 1992) and other Brassica species are regarded as being able to tolerate relatively high chloride concentrations (Kemmler, 1985). Thus, oilseed rape can be regarded as relatively well adapted for such conditions in comparison to many another crops. Under field conditions chlorine deficiency does not occur because most of the soils contain or receive enough Cl with K fertilizers as well as from other sources.

Most of the soils contain enough iron for crop production. Nevertheless, iron deficiency can appear due to impaired availability, particularly on calcareous soils or under soil conditions of oxygen shortage and accumulation of CO_2^{--} and HCO_3^-. Potassium deficiency may induce and intensify Fe deficiency in plants. Special deficiency symptoms for oilseed rape have not been described. General symptoms of Fe shortage in plants are intercostal chlorosis of younger leaves with yellowing of the interveinal area whereas the veins remain dark green. From other species, it is well-known that varieties show big differences in relation to to sensitivity to iron deficiency.

5. Nutrient requirement of oilseed rape

5.1. Total uptake and pattern of uptake during the course of growth

Nutrient uptake by oilseed rape depends considerably on species, variety type (winter-/ spring-), yield, dry matter development, and nutrient and water supply. In high yielding areas for example in Central Europe where winter rape varieties are grown, a high amount of dry matter, of 2-3 t/ha DM, is already produced in autumn before the start of winter. For such development to take place there must be besides all other growth factors a sufficient supply of water and nutrients from the soil or from fertilizers. Substantial quantities of nutrients are required. Nutrient uptake before winter amounts about 50-100 kg/ha of nitrogen and potassium and 20-40 kg/ha of calcium and phosphorus (Orlovius, 1984; Merrien *et al*., 1988; Barraclough, 1989; Merrien, 1992; SCPA). In hard winters with many frosty days, a substantial proportion of the leaves is killed by frost and is lost from the plant. In such cases, measured nutrient uptake in autumn is higher than in spring and the uptake curves decline from winter to spring.

At the beginning of growth in spring nutrient uptake starts early and is intensive. This is particularly the case for potassium which from the start of vegetative growth in spring until flowering, shows highest daily uptake rates of between 6 and 12 kg/ha/day K_2O. In many cases, the demand of winter rape for K in particular is underestimated with a total amount of 350-450 kg K_2O/ha required for a seed yield 3.5 t/ha (Fig. 15).

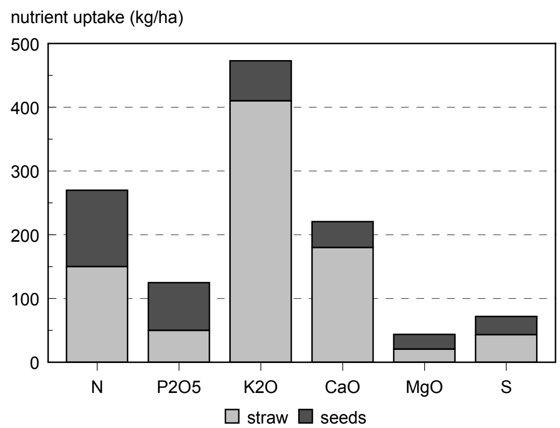

Fig. 15. Total uptake of macronutrients of oilseed rape (Merrien *et al*., 1988).

Nearly all other nutrients are taken up rather steadily from spring until maturity. In comparison to cereals the total nutrient amounts taken up by oilseed rape are considerably higher with 200-300 kg/ha N, 90-130 kg/ha P_2O_5, 50 kg/ha MgO. The well-known high sulphur requirement of rape and the high sensitivity of this crop to S-deficiency is clear from the high sulphur uptake of 50-70 kg/ha S. The demand for micronutrients is relevant (Fig. 16) and must be taken into account in establishing a well developing crop.

Additional to nutrient uptake by the aerial plant parts, rape plants also need about 10% of the shoot nutrients for root formation (SCPA).

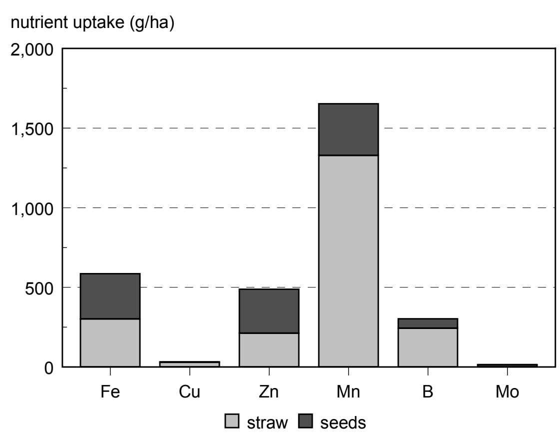

Fig. 16. Total uptake of micronutrients of oilseed rape (Merrien *et al*., 1988).

From Figure 17, it can be clearly seen that the supplement of the nutrient demand is prerequisite for dry matter formation: The uptake of nearly all nutrients particularly of N, P and K precedes dry matter production. Young plant cells must contain a high concentration of nutrients required for enzyme activation and to initiate growth processes.

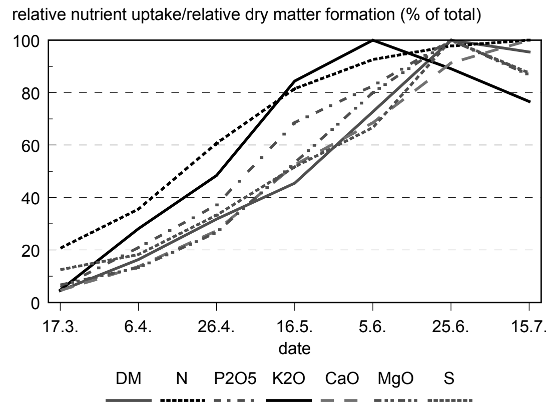

Fig. 17. Uptake of macronutrients and dry matter (DM) formation of oilseed rape during the vegetative period (SCPA).

From the uptake curves it is obvious that there are differences in uptake pattern between the various nutrients. Whereas for potassium the main uptake period ends as soon as flowering is over, nitrogen, sulphur and magnesium show a regular and continuing uptake almost until maturity.

Similar differences can be observed between micronutrients (Fig. 18). Zinc, boron and copper are taken up comparatively early and uptake is continued until maturity whereas iron, copper and manganese are absorbed with a maximum at the flowering stage, then the uptake curves decline because the nutrients are lost from the plant by leaf fall.

The distribution of particular nutrients between the diverse plant organs differs depending on the various physiological tasks of the nutrients and translocation processes. The distribution of nutrients does not need to be identical with that of dry matter within the various plant parts. During the growth period, considerable nutrient retranslocation takes place within the plant organs (Merrien *et al.*, 1988).

From spring until the flowering stage most of the nutrients are stored in the leaves but as the plant develops the uptake patterns of the diverse nutrients show increasing differences. For example increasing quantities of potassium are transferred from the leaves into the stems, and at the ripening stage about 60% of the total potassium is stored in the stems whereas only small amounts of K can be found in the seeds at maturity. Also for nitrogen, phosphorus and sulphur considerable quantities are stored in the stems but are then retransfered into the seeds (N, P) or remain in the pods (Mg, S) (s. Table 17).

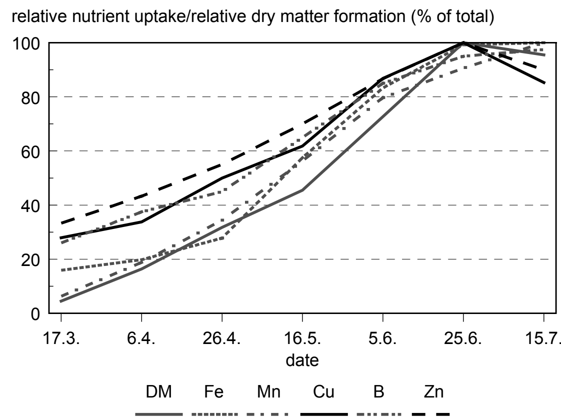

Fig. 18. Uptake of micronutrients and dry matter (DM) formation of oilseed rape during the vegetative period (SCPA).

Varietal differences can influence nutrient distribution within plants. For sulphur, it is well-known that uptake pattern of the new 00-varieties low in glucosinolates differs from the older ones even though total S uptake is almost the same between varieties. In the 00-varieties sulphur is concentrated in the pods and only very small amounts of S-containing glucosinolates are translocated into the seeds during the ripening period (Fig. 19).

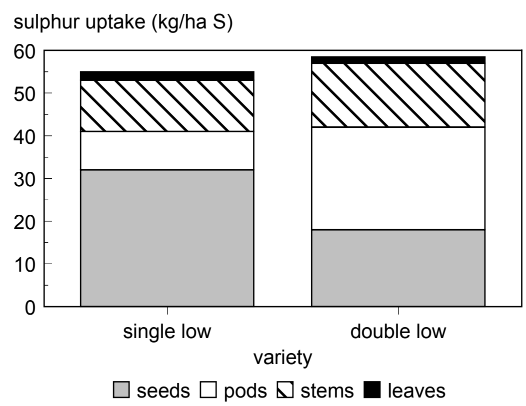

Fig. 19. Sulphur uptake of different plant parts of single and double low oilseed rape varieties at harvest (Schnug and Haneklaus, 1993).

The S concentration in the pods of 00-varieties are much higher than in the seeds in contrast to the old 0-varieties where considerable S quantities move into the seeds (Schnug and Haneklaus, 1993).
The micronutrients show similar differences in uptake patterns as for the macro-elements. For copper, manganese, boron and molybdenum a considerable portion of the total uptake remains in the pods with only small quantities translocated into the seeds (Merrien *et al*., 1988). Only zinc is transported in relatively high amounts into the seeds, with about 40% of the total Zn uptake located in the seeds at maturity.
Thus, there are big differences between total nutrient uptake and export from the field if the straw remains on the field (Figs. 15 and 16). Although nutrient export from the field with the seeds is lower than the total uptake of the whole plants, the complete demand of the rape crop must be met during the growth period. If only the seeds are harvested the remaining nutrients from the crop residues have to be taken into account within the nutrient balance of the entire crop rotation and the nutrient demand of the following crop. It is particularly obvious for potassium that although the total demand is very high, the removal from the field of only the seeds means that it is relatively low in comparison to nitrogen, phosphorus or sulphur. Nevertheless, these high K-amounts must be available, otherwise plant growth and dry matter production are reduced. Of the micronutrients particularly manganese, boron and molybdenum over 70% of each of these nutrients is located in the straw whereas iron and zinc are concentrated more in the seeds (Fig. 16).
The nutrient uptake data are all given for high yielding winter varieties in Central Europe and show the importance of an adequate supply of rapidly available nutrients to establish a high yield. Of course, nutrient uptake depends on the yield produced and other factors. Therefore in regions which are subject to other conditions, and in which other varieties are grown and lower yields obtained other nutrient uptake data are reported. For example for a 2 t/ha yield with a spring rape variety in Canada a nutrient removal of 120 kg/ha N, 50 kg/ha P_2O_5, 95 kg/ha K_2O, 25 kg/ha S was measured (Bailey and Grand, 1992). The nutrient uptake of a 1.5 t/ha mustard on the Indian continent lay around 80 kg/ha N, 40 kg/ha P_2O_5, 85 kg/ha K_2O, 25 kg/ha S and 20 kg/ha MgO (*In*: Pasricha and Tandon, 1993).

5.2. Optimum nutrient content in plants

Numerous authors have published data giving optimum nutrient concentrations of plants made by plant analysis. The ranges of adequate nutrient contents taken from various reviews mostly show similar values for specific nutrients (Tables 15 and 16). Deviations from these values can be attributed to differences in time of sampling (stage of development) and different plant organs. Furthermore, varietal differences and site specific conditions can influence the optimum nutrient range. For interpretation of plant analysis data it is important to compare the analyzed values on equal terms in relation to sampling time and plant part analyzed.

Table 15. Optimum (adequate) concentration of macronutrients in oilseed rape (*Brassica napus*) - Plant analysis data.

Analyzed plant organ	Sampling time (stage of development)	% in DM						Author
		N	P	K	Mg	Ca	S	
fully expanded leaf on the main stem	beginning of elongation	5.5	0.58	2.5	0.12	1.1	0.53	Merrien (1992) winter variety
whole above-ground part of plant	flowering stage	3.2	0.40	2.5			0.5	Bailey and Grant (1992) spring variety
just fully developed leaves when crop is 30-50 cm high	beginning flowering stage	4.0-5.5	0.35-0.7	2.8-5.0	0.25-0.4	1.0-2.0		Bergmann (1992) winter variety
young, fully developed leaves of the upper third of the plant	shooting stage	4.2-5.5	0.4-0.6	2.2-3.0	0.15-0.25	1.0-1.5	0.55-.65	Cramer (1990) winter variety
fully developed leaves	beginning flowering stage	4.0-5.4	0.32-0.66	2.4-4.9	0.19-0.39			Kerschberger and Franke (2001)
palm-big leaves	20-30 cm high	4.0	0.35	3.0	0.2	1.0	0.5	LUFA Kiel (1998)
upper 3 most recently mature leaf blades	pre-flowering	3.3-6.4	0.34-0.69	2.9-5.1	0.21-0.62	1.4-3.0	0.5	Reuter (1986)
fully developed leaves	middle shooting stage	4.0-6.0	0.35-0.7	2.5-5.0	0.2-0.4	1.0-2.0	0.5-0.8	Finck (1998)

Table 16. Optimum (adequate) concentration of micronutrients in oilseed rape (*Brassica napus*) - Plant analysis data.

Analyzed plant organ	Sampling time (stage of development)	ppm in DM						Author
		Fe	Mn	Zn	Cu	B	Mo	
fully expanded leaf on the main stem	beginning of elongation	125	41	37.5	4.5	23	0.6	Merrien (1992) winter variety
just fully developed leaves when crop is 30-50 cm high	beginning flowering stage		30-100	25-70	5-12	30-60	0.4-1.0	Bergmann (1992) winter variety
young, fully developed leaves of the upper third of the plant	shooting stage	50-80	25-40	25-35	4-6	30-50	0.4-0.6	Cramer (1990) winter variety
fully developed leaves	beginning flowering stage		22-150			19-60	0.32-0.9	Kerschberger and Franke (2001)
palm-big leaves	20-30 cm high	50	35	25	6	30	0.4	LUFA Kiel (1998)
upper 3 most recently mature leaf blades	pre-flowering		31-250	22-49	4-25	22-54	0.28-0.55	Reuter (1986)
fully developed leaves	middle shooting stage	50-150	40-150	25-70	5-10	25-50	0.4-0.8	Finck (1998)

According to Merrien *et al*. (1988) large variations in nutrient concentrations can be found between the various plant organs. Moreover each nutrient behaves quite differently. Whereas for example leaves and buds contain a high nitrogen and phosphorus concentration at the flowering stage the stems show a relatively low N and P content (Table 17). For potassium, however, distribution is again different with high concentrations in the stems and leaves but a low content in the buds. At the ripening stage stems and pods reveal only low concentrations of nitrogen and phosphorus but high contents of these nutrients in the seeds whereas the behaviour of potassium is reversed with a high concentration in the stems and pods but a low content in the seeds.

Additionally, deficiencies and excesses of particular nutrients can influence the content of other specific nutrients. This can possibly lead to misinterpretation of determined values. For example, in a fertilizer trial on a S deficient soil the lack of sulphur depressed the seed yield considerably. The deficiency of sulphur led to a nutrient build-up in the shoot with excessive nutrient concentrations. With a two-fold foliar application each of 25 kg/ha epsom salt, growth conditions were significantly improved and resulted in a yield increase of 1.41 t/ha. This treatment simultaneously brought about a considerable reduction of the N, P, Mg, B, and Mn content of the upper leaves (Table 18).

Table 17. Nutrient content (% in DM) in different plant organs of oilseed rape at the flowering and ripening stages (Merrien *et al*., 1988).

	Flowering stage			Ripening stage		
	stems	leaves	buds	stems	pods	seeds
N %	2.27	4.00	5.27	0.58	0.58	3.67
P %	0.50	0.42	0.93	0.05	0.14	0.66
K %	4.20	4.23	2.73	3.37	2.63	0.99
Ca %	0.62	2.83	1.03	0.84	2.03	0.56
Mg %	0.09	0.09	0.26	0.05	0.08	0.27

(Variety Bienvenue).

Table 18. Influence of a sulphur foliar fertilization on the yield and the nutrient content of oilseed rape on a sulphur deficient site.

Foliar fertilization with epsom salt kg/ha S	Seed yield t/ha	Nutrient content in the upper leaves (in DM)					
		N %	K %	Mg %	S %	B ppm	Mn ppm
0 (control)	2.91	6.34	3.11	0.28	0.30	32	34
2 × 3.25	4.32	5.42	2.19	0.23	0.30	18	26
2 × 3.25 + B + Mn	4.46	5.54	2.03	0.22	0.29	21	26

For this reason, it is obvious that careful sampling is a prerequisite and necessary to obtain a representative value for the nutritional status of the rape crop and to compare the determined field values on the same basis as the threshold values from tables in the literature.

6. Effect of fertilizer use on yield and quality

The nutrient demand of oilseed rape is considerably higher than that of cereals. High yields can only be realized if the special characteristics of this crop are considered. Although oilseed rape develops an impressive root mass, ability to take up nutrients is not always high. The main period of nutrient uptake often occurs when soil temperatures are low so that uptake conditions are generally poor.

For winter varieties sufficient quantities of nutrients must be available in autumn because the crop must produce about 2-4 t/ha of dry matter by winter in order to achieve high seed yields (s. chapter 5). All the necessary prerequisites for seed yield formation are established during this period. The aim is thus to produce a plant with a fully developed rosette with 8-10 leaves with a vigorous root system before winter.

6.1. Nitrogen

The nitrogen supply of oilseed rape is of central importance to ensure high yields. As all Brassica-species, oilseed rape has a high N-demand (of about 200-300 kg/ha N) depending on the type of subspecies and yield. Success in obtaining high seed yields lies in establishing the right quantities on N fertilizer and when they should be applied.

6.1.1. N fertilizer recommendations in autumn

Plants of winter rape types should be well supplied with nutrients by the end of the vegetative period in autumn but excess should be avoided. Nitrogen uptake before winter is often in the region of about 60-100 kg/ha N that must be provided by the soil or fertilizers. Whether N fertilization in autumn is required depends on several factors which influence plant development. Much experience is needed to calculate the right input of N fertilizer especially under atypical weather conditions.

Generally under optimum conditions leading to optimum plant development, N fertilization is not needed as early as in autumn. Too high a supply of N in autumn leads to an unwanted intensification of growth with premature stem formation and to too great a number of leaves with the consequence of increasing risk of frost damage and rotting of the vegetative cone during winter. Thus under optimum conditions (early sowing, best soil cultivation, adequate N supply from the soil or from the pre-crops such as legumes) additional N application in autumn is unnecessary.

The application of N fertilizer in autumn should be considered under all conditions under which growth is delayed before winter. On poor sites where there is a low N supply or N release, an application of N can be beneficial. N availability in the soil can be depressed by dry weather and cold temperatures after sowing, as well as by high rainfall in late summer to September or by poor soil structure. Straw incorporation from the pre-crop may also lead to a considerable fixation of N in the autumn. The more these factors come together to decrease N availability, the greater the need for an application of N fertilizer in autumn of up to 70 kg/ha N. The assimilates of the oldest leaves serve as a nutrient source for the supply of the root system. Buds for the side shoots are formed at the 6- to 8-leaf-stage. These are essential for optimum development of lateral branching and flower buds.

Time of application depends on a number of factors. For crops sown early the decision can be made up the 4-leaf-stage. Following incorporation of large quantities of straw it makes good sense to apply some starter N to the rotting straw. If the sowing date is delayed, at least a part of the total N rate should be applied directly at sowing. Any N fertilizer should be applied at the latest by the end of September. Applications of N made too late delay the growth break which occurs in autumn and result in high concentrations of non assimilated N compounds in leaves and stems which reduce frost resistance.

6.1.2. N fertilizer recommendations in spring

In spring with the new start of growth the rape plant mobilizes assimilates and nutrients from assimilate reserves stored in leaves and stems in autumn, to produce a well developed root system and enough leaves and side branches. The number of lateral branches is a fundamental yield characteristic influencing the number of pods per plant and depends on the number of leaves which can be constituted before the onset of shooting. For this reason, the most important aim of all treatments in spring should be to develop an adequate number of lateral branches in the rape plants.

Nitrogen fertilization significantly regulates the development of the rape crop. As a general guide value the nitrogen demand of 1 t/ha seed including straw can be calculated as 60 kg N/ha. Thus, for a seed yield target of 3.5 t/ha oilseed rape has a arithmetic nitrogen demand of 210 kg/ha N. However, to determine the necessary N fertilizer rates in the spring further site parameters must be considered besides the mineral content in the soil such as the expected yield, soil texture, content of soil organic matter, organic fertilization or crop formation after winter (for winter varieties). The rate of N application in spring depends therefore on several factors:

- yield potential (60 kg N/t seed yield),
- mineral N content in the soil,
- N mineralization of soil organic matter and crop residues during the growth period,
- plant development before winter i.e. before start of spring growth,

- site conditions (soil type and texture, rainfall and rainfall distribution),
- varietal differences,
- N rate in autumn,
- leaf loss during the winter period.

Thus, the first step of a site-specific N fertilizer recommendation should be the calculation of the crop N demand depending on the attainable seed yield (60 kg N/t seeds). As a second step the available nitrogen supply of the soil must be estimated and must be subtracted from the total N demand of the crop. The soil mineral nitrogen (NO_3-N, NH_4-N) can be easily measured by soil analysis and is potentially available for crop uptake. The nitrogen mineralized from the soil organic matter during conversion of organic N to mineral N is difficult to estimate because of the many influencing factors. This contribution of mineralization can be large on organic and peaty soils, on fields where organic manures have been used for several years or where nitrogen rich crop residues have been left after the harvest of the pre-crop.

On the other hand, nitrogen losses by leaching, denitrification or ammonia volatilization must also be considered. Much experience and the results of many fertilizer experiments under different conditions are necessary to assess guide values for site specific recommendations.

Table 19. N fertilizer recommendation system for winter rape (Germany).

Guide value for 2.5-4 t/ha: 200 kg/ha N (fertilizer N incl. available N-content in the soil (NO_3-N and NH_4-N))
site specific correction of the guide value:

Supplements	Reductions
+30 kg/ha N at a yield level over 4 t/ha	-30 kg/ha N at a yield level below 2.5 t/ha
+20 kg/ha N for sandy soils poor in organic matter	-20 kg/ha N on soils rich in organic matter
+30 kg/ha N on cold clay soils	-20 kg/ha N after set-a-side with leguminosae
	-20 kg/ha N after regularly use of organic fertilizers
+20 kg/ha N at poor crop formation after winter	-20 kg/ha N at good crop formation after winter

The sum of supplements and reductions should not exceed 40 kg/ha N.

For example, in the German N recommendation system, the N fertilizer rate is based on the N demand of the crop and the nitrate content of the soil (0-90 cm), measured by soil analysis or estimated from the course of precipitation and temperature during the winter season (CA Hannover, 1998). For a yield range of 2.5-4 t/ha, a guide value of 200 kg/ha N must be supplied by the soil and fertilizer N. This guide value is related to the total N demand of oilseed rape to reach the economic yield optimum and has been established from the results of many fertilizer trials with different site conditions. To calculate the fertilizer N, the mineral N content of the soil must be subtracted from this guide value. The guide value of 200 kg/ha N is further adapted by supplements or reductions depending on specific site conditions (Table 19). Nitrogen from organic fertilizers (slurry, manure) has to be subtracted to obtain the mineral N fertilizer rate.

6.1.3. Time of N application

For crop stands in which the minimum number of 8 leaves per plant has not been achieved in autumn, all should be done to encourage the formation of new leaves since this is the prerequisite for the production of an adequate number of lateral branches. In such cases, enough nitrogen must be available very early during the vegetative period. For plants in which there has been optimum development in autumn and where little damage has occurred during the winter, bud formation of the lateral branches must also be encouraged. For this reason the N demand of rape is earlier than that of cereals. Especially for early varieties in which stem formation to some extent begins at a very early stage, there is a need for an early available N supply. Therefore, the first N applied should be before start of vegetative growth to ensure that it is available once growth starts. At the stage from the end of leaf formation until the onset of shoot development, the available starter nitrogen protects the plant against the loss of lateral shoots and protects pod formation.

During the stages of shoot development to flowering, bud loss and bud and flower fall must be avoided. This takes place if the plants are insufficiently supplied with assimilates and nutrients. Up to flowering for optimum rape development, there must be an uptake of about 180-220 kg /ha N (60 kg N per t seed yield).

From the start of flowering about 100 kg N/ha must be transferred into the pods within two weeks. About 5 kg/ha N per day can be taken up from the soil, 40-60 kg/ha N must be retranslocated from the leaves and stems to the pods. Fewer pods are produced if the requirement of these amounts of N cannot be met because of insufficient N supply or/and inadequate retranslocation as a consequence of too low a supply of energy (cold and cloudy weather).

The total quantities of fertilizer needed of 180-220 kg/ha N are normally divided into two applications, with about 50-60% being given in the first application. Only on very high yielding sites or on fields with a very high N demand (> 200 kg N/ha) is it of benefit to split the total N applied into 3 single applications (Fig. 20). In such cases the main N quantities should be given in the first (45%) and second application (35%) whereas the third application should be comparatively low (40-60 kg/ha N).

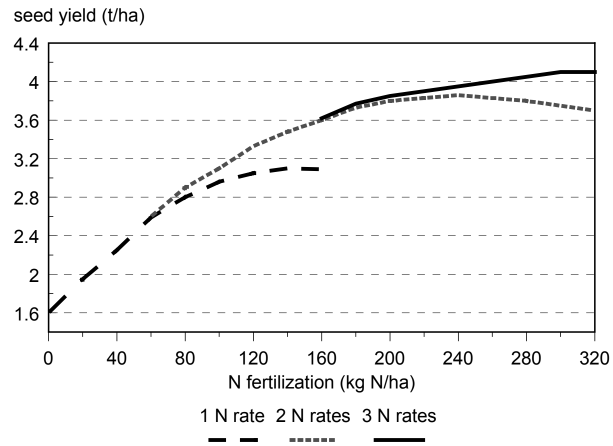

Fig. 20. Effect of different N-fertilizer doses and number of N-applications on seed yield of oilseed rape (Hanus and Sieling, 1998).

However, it is necessary to obtain a maximum yield without decreasing the oil content. In the experiments in Fig. 20 the first N application was made at the start of growth, the second at the start of shooting (EC 31) and the third at the late bud stage (EC 55). In field experiments with new high yielding hybrid-varieties, it has been concluded that the second N application should be increased by an amount of 20-30 kg/ha N in comparison to a conventional variety to benefit from the higher yield potential (Sauermann, 2000).

Besides yield benefits splitting the total N fertilization into a number of applications has further advantages:

- nutrient leaching can be reduced especially on sandy soils,
- early lodging can be avoided,
- after a possibly necessary new sowing as a consequence of hard frost damage the choice of the following crop is easier,
- the total N fertilization can be better adjusted to changes of weather and growth conditions.

Only where the total N fertilizer rate of application lies under about 100 kg /ha N is one application sufficient.

6.1.4. N/S interaction

Because of the central role of nitrogen and sulphur in the synthesis of proteins, the supplies of N and S for oilseed rape are highly interrelated. Large doses of nitrogen may enhance sulphur deficiency because of higher growth rates of the youngest and middle leaves (Blake-Kalff *et al.*, 1998). With insufficient nitrogen supply buds and also pods already pollinated may die and fall from the plant. The number of seeds per pod is scarcely influenced by N nutrition compared to the effect of a sulphur deficiency. Low S supply limits the seed number per pod even when nitrogen nutrition is adequate especially in the upper parts of the plants. Because of the influence of sulphur on protein formation S deficiency increases the effect of nitrogen deficiency and intensifies N deficiency symptoms. If the S deficiency is not recognized and misinterpreted as nitrogen deficiency, and nitrogen fertilization increased, as may well occur, there is a disasterous consequence by further increased sulphur deficiency.

Rape plants grown under both N and S deficiency conditions show fewer S-deficiency stress symptoms. Increasing the N fertilization speeds up growth and therefore leads to an increased demand for sulphur. The internal balance between N and S becomes disturbed. In a pot experiment, moderate and high rates of N application suppressed seed production at low rates of S application. When S was limiting, N accumulated as nitrate in the vegetative parts of the plants. Maximum yields were observed only with simultaneous application of high rates of N and S. Seed yield response to nitrogen was dependent on the balanced availability of sulphur (Janzen and Bettany, 1984a).

Such results have been confirmed by field trials in Scotland with winter rape. On a low sulphur site the increase of the N fertilizer rate from 150 to 250 kg/ha N decreased the seed yield of two 00-varieties without sulphur fertilization (Walker and Booth, 1994). However, with an addition of 64 kg/ha S, the higher nitrogen supply led to an increase in seed yield (Fig. 21). This interrelation of nitrogen and sulphur makes it very clear that the nitrogen and sulphur supplies in particular must be balanced to achieve optimum yields.

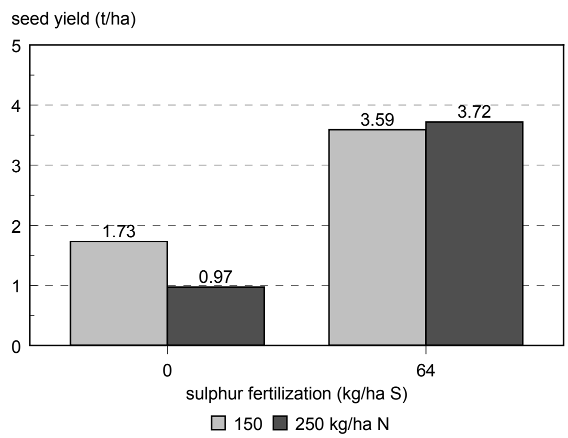

Fig. 21. Interaction of nitrogen and sulphur fertilization on the yield of oilseed rape (Walker and Booth, 1994).

6.1.5. Quality

6.1.5.1. Oil content

As a major nutrient, nitrogen has not only a considerable effect on yield formation but also on seed quality of oilseed rape. The most important quality factor is the oil content which is, however, linked to the protein content. In an extensive two years trial program in Western Australia, increasing nitrogen fertilizer rates led in both years to rising seed yields. In all experiments, in both years, there was no relationship between the seed yield and the oil- or protein-content. However, the concentration of oil in the seeds decreased with an increase of the protein content (Brennan *et al*., 2000). The addition of the oil plus the protein concentration in the seeds in both years was approximately constant with a value of 62%. With an increase for each 1% in the protein content the percentage of oil declined by 0.8-0.9% (Fig. 22).

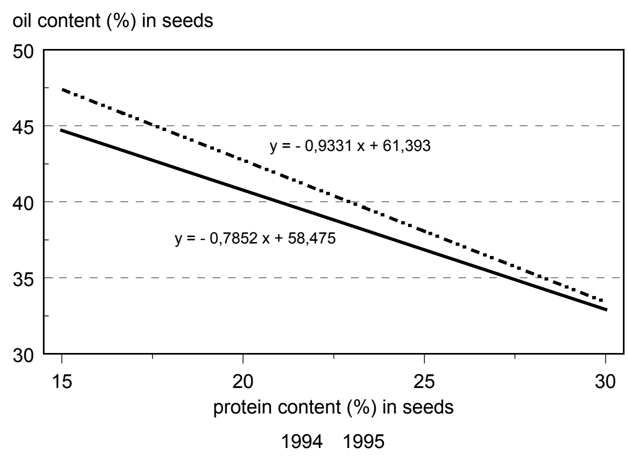

Fig. 22. Relationship between the protein and oil content of the seed of oilseed rape for two years (Brennan *et al*., 2000).

The oil content of seeds tended to decline with increasing N fertilizer rates. These results are confirmed by several other authors summarized from Holmes (1980) in an older report, but have also been confirmed in recent investigations. This relationship seems to be independent of the kind of rape crop and was found in winter and summer rape, Indian mustard, sarson, brown and white mustard (Zhao *et al*., 1993a; Taylor, 1991; Ahmad *et al*., 1998; Kachroo and Kumar, 1999). However, the oil yield as the main important yield parameter increased and runs to a large extent parallel with the seed yield (Fig. 23).

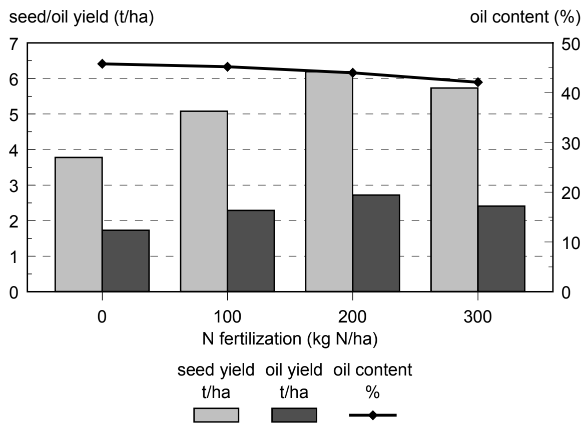

Fig. 23. Influence of increasing N application on seed yield, oil yield and oil content of oilseed rape (Zhao *et al*., 1993a).

6.1.5.2. Glucosinolate content

The effects of applying nitrogen on the glucosinolate concentration in the seeds may be variable. The level of glucosinolate content depends mainly on site and variety. Generally, under optimum growth conditions nitrogen slightly increases the glucosinolate concentration of the seeds (Forster, 1977; Bilsborrow *et al*., 1993). However, under S deficient conditions, increasing N supply results in a decrease of glucosinolate content whereas under S sufficient conditions nitrogen has the opposite effect (Zhao *et al*., 1997). Fig. 24 shows the interactive effect of nitrogen and sulphur on a S-deficient site.

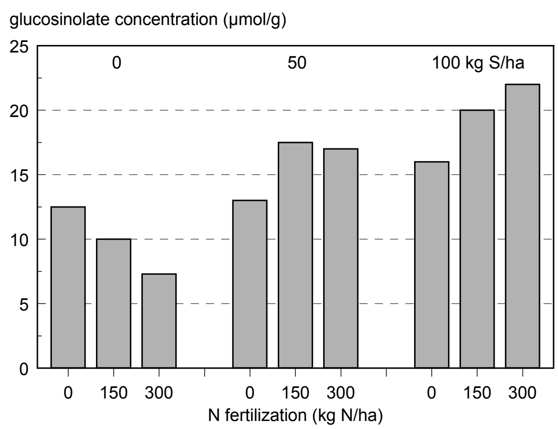

Fig. 24. Effects of nitrogen and sulphur on the concentration of glucosinolates in the seeds of oilseed rape on a S deficient site (Zhao *et al*., 1997).

In the S deficient plants, sulphur is mainly incorporated into proteins and less is available for glucosinolate synthesis. When S supply is sufficient, increasing N increases both protein- and glucosinolate-S.

Varieties with a high glucosinolate content react more sensitively than the new 00-varieties (Walker and Booth, 1994). On a low sulphur site, the increase from 150 to 250 kg/ha N led to a decrease in the glucosinolate content of 71% in a 0-variety whereas for the two 00-varieties which were far lower in glucosinolate a decrease of only 38% and 2% was found (Fig. 25).

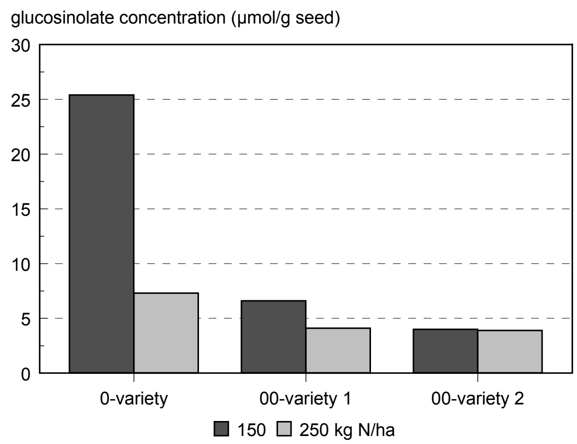

Fig. 25. The effect of nitrogen on the glucosinolate content of oilseed rape on a low sulphur site (Walker and Booth, 1994).

6.1.6. Nitrogen fertilizers

Rape needs nitrogen very early. The temporary very intensive nitrogen uptake of oilseed rape requires high availability and a predictable effect of the applied N fertilizer. In some cases therefore plants should receive an early application in the highly available nitrate form to support lateral branching and the development of shoot buds. This is the case particularly for rape crops cultivated on soils with a poor structure, with a delayed nutrient mobilization, or for early varieties and especially for weakly developed plants. On many sites nitrogen is given as ammonium nitrate so that with this N form the nitrate demand of the plants is also satisfied.

Generally the effect of the main N fertilizers used worldwide, ammonium nitrate and urea, seems to be rather similar on oilseed rape. For very early application dates and under unfavorable weather conditions (dry, hot, windy), considerable gaseous N-losses from urea have to be taken into account. Under low temperatures and dry conditions the rate of transformation from urea to the plant available ammonium and nitrate forms is rather low delaying the effect of N fertilization.

In some European countries, a liquid N form of ammonium nitrate urea solution (28-30% N) is also commonly used. It has a comparable effect to ammonium nitrate due to the presence of nitrate as well as ammonium (about 25% NO3-N, 25% NH4-N, 50% Amide-N). This N fertilizer is applied in liquid form using a sprayer. Some special use instructions have to be considered because young rape leaves are highly sensitive and leaf damage can occur under unfavorable conditions, particularly in the case of low temperatures. If ammonium nitrate urea solution is used as a foliar fertilizer for a necessary very rapid N response it is often combined with fungicides or insecticides which often has the advantage of reducing pesticide application rates. To avoid leaf damage a water : fertilizer ratio of at least 3:1 is recommended together with the use of special kinds of nozzles for the spreaders. The use of ammonium sulphate nitrate or ammonium sulphate has the advantage of providing both nutrients nitrogen and sulphate in the one fertilizer.

6.2. Sulphur

Rape crops as members of the Cruciferae are well acknowledged as plants with an especially high sulphur requirement and are particularly sensitive to S deficiency. Authors from all continents have reported on the need of sulphur fertilization for the oilseed rape crop (i.e. Bailey, 1986; Schnug and Pissarek, 1982; Tandon, 1993; Good and Glendinning, 1998; Gupta and Dubey, 1998; Matthey *et al*., 2000). The increasing attention which has been given to sulphur as a plant nutrient in the industrialized countries arises from the declining levels of atmospheric sulphur deposition from air and rain to values below 10 kg/ha S as a consequence of “clean air” policies. In other countries, sulphur was and is well recognized as a major nutrient in plant production. Nevertheless, deficiency symptoms are widespread and lack of sulphur restricts yields in many areas. Moreover, mild S deficiency in which no visible deficiency symptoms are apparent can still reduce plant growth and seed yield.

In a four year S fertilizer trial program with winter-rape in Germany, yield responses of 0.3-0.5 t/ha (Fig. 26) were reported as a result of S-application (Matthey *et al*., 2000). On average from 33 experiments a S rate of 20-30 kg/ha S was sufficient for optimum seed yields. In most experiments no or only few visible deficiency symptoms were apparent. However, on sites with severe S deficiency yield losses were much higher and optimum S rates rose considerably up to 70 kg/ha S. S fertilizer treatments were especially effective when root growth was inhibited by poor soil structure and soil compaction. On sandy soils with a low humus content and with high rainfall during the winter period, a high response to sulphur fertilization was found as a consequence of S leaching and low S release.

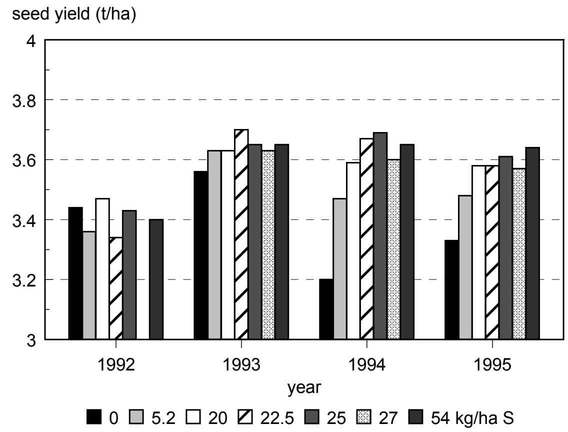

Fig. 26. Effect of increasing rates of sulphur application on the seed yield of winter rape (*Brassica napus*) in four different years (Matthey *et al*., 2000).

S fertilizer trials in other continents and with other rape species show similar results regardless of yield. Under dryland conditions in India with a relatively low yield of 1 t/ha seed yield of mustard a response of 55% was obtained at a rate of 30 kg S/ha (Raj *et al*., 1998). In other investigations with *Brassica juncea* and *Brassica campestris* genotypes (Fig. 27) with a very high yield of 6-7 t/ha, a sulphur rate of 40 kg S/ha led to optimum seed yields in both species whereas 60 kg S/ha already brought about a small yield decrease (Ahmad *et al*., 1998).

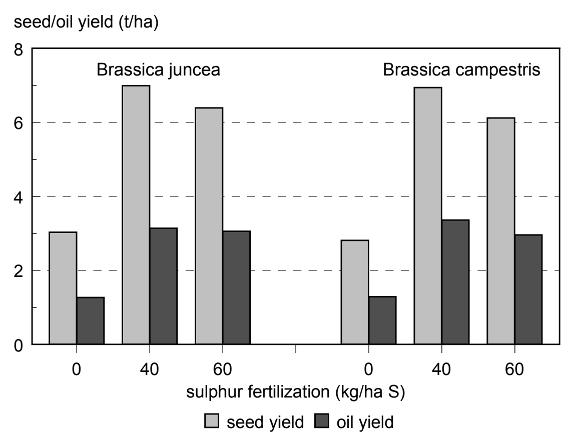

Fig. 27. Effect of increasing S fertilization on the seed and oil yield of *Brassica juncea* and *Brassica campestris* at 100 kg/ha N (Ahmad *et al*., 1998).

Leaf area index and rate of photosynthesis were considerably increased by the sulphur fertilization.

In a summarizing report of Pasricha *et al*. (1987) which included different states of India, the yield response to sulphur application varied between 12 and 48% (irrigated) and 25-124% (rainfed) with yields on the control plots between 0.4 and 2.6 t/ha.

6.2.1. Sulphur and nitrogen efficiency

Pot trials underline the importance of sulphur for a high N efficiency. With increasing S content of rape leaves from 0.2 to 0.65% S utilization of fertilizer N was enhanced from 6 to 25% (Schnug *et al*., 1984). In other pot trials the apparent N use efficiency rose from 25 to 40% with increasing S supply. In field trials on an alkaline soil high in organic-N and organic-S increasing S rates from 0 to 75 kg/ha S improved the apparent N use efficiency from 40 to 50% (Fismes *et al*., 2000).

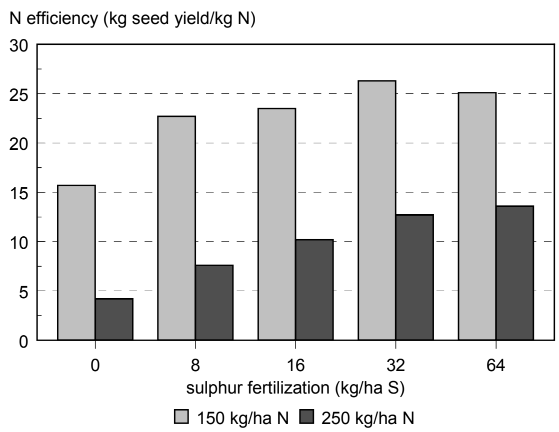

Fig. 28. Effect of sulphur supply on the nitrogen efficiency of oilseed rape (average of two 00-varieties, data from Walker and Booth, 1994).

From these results, it is obvious that sulphur improves nitrogen efficiency. Under conditions of sulphur deficiency the nitrogen supply cannot be sufficiently converted in biomass. In investigations of Walker and Booth (1994) with two levels of N fertilizer increasing S fertilization from 32-64 kg/ha S enhanced seed yield per kg N used (Fig. 28). This finding is of particular importance for areas where S deficiency is not correctly recognized. Where sulphur deficiency is mistaken for N deficiency and additional nitrogen applied, not only is there a larger yield loss but there is also an environmental hazard as the N not taken up by the crop can be leached as nitrate into the subsoil and possibly into the groundwater.

6.2.2. Quality

6.2.2.1. Oil content

In many field trials which show high yield responses to S fertilization, also report increases in oil content, whereas in field trials with a low or without a yield increase, oil concentration remains unaffected. This relationship becomes particular clear in an Australian experiment where the effect of sulphur on yield and quality of *Brassica napus* was tested following different preceding crops (Fig. 29). Rape following cereals showed only a small yield response of 0.4 t/ha to sulphur application and the oil concentration was raised by 0.4% (absolute). However, with a high yield response after pasture the effect of sulphur on rape was much higher with a response of 1.3 t/ha. Consequently the oil content was increased by 3% (absolute) (Good and Glendinning, 1998).

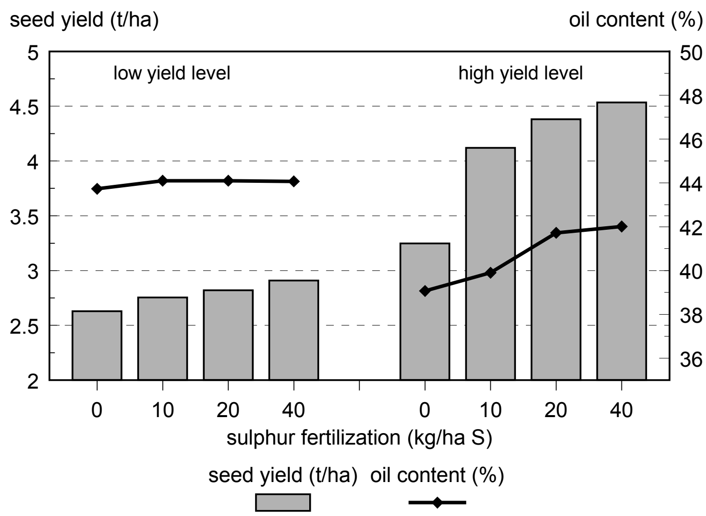

Fig. 29. Effect of sulphur fertilization on seed yield and oil content of *Brassica napus* at different yield responses (Good and Glendinning, 1998).

In many Indian publications, the beneficial effect of sulphur on oil content of mustard has been described (Gupta and Dubey, 1998; Khan and Husain, 1999; Jain and Gupta, 1996; Tandon, 1993; Triveti and Sharma, 1997; Mahal *et al*., 1997). Especially under severe S deficiency the increase of the oil content becomes considerably high with an absolute response of 4 to 6% (Pasricha *et al*., 1987; Ahmad *et al*., 1998), (Fig. 30).

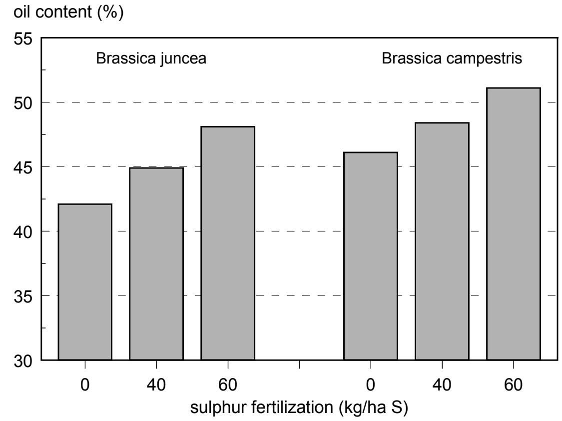

Fig. 30. Influence of increasing sulphur supply on the seed oil content of *Brassica juncea* and *Brassica campestris* (Ahmad *et al*., 1998).

Despite a strong N/S interaction in relation to seed yields (s. chapter 6.1.4), only a small N/S interaction effect can be observed on the oil content (McGrath and Zhao, 1996). In British field experiments on S deficient sites, sulphur fertilization increased seed oil content significantly at all nitrogen levels between 100 and 230 kg/ha N (Fig. 31). The increase in oil content due to S application was only slightly lower at the highest N level. In the absence of sulphur deficiency, sulphur application does not influence the oil content of the seeds regardless of the nitrogen supply (Zhao *et al*., 1993a).

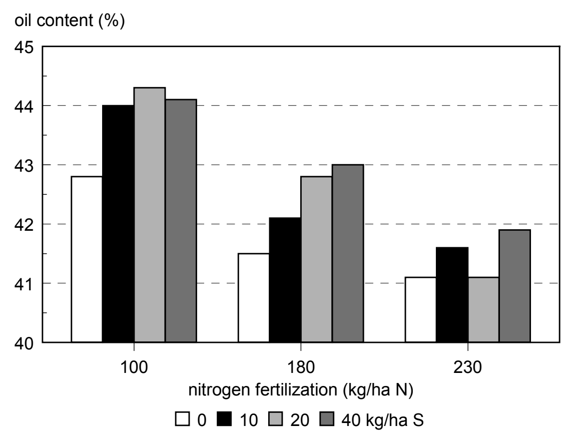

Fig. 31. The effects of nitrogen and sulphur fertilization on seed oil content of winter oilseed rape (McGrath and Zhao, 1996).

6.2.2.2. Glucosinolates

The content of glucosinolates is of particular interest in the oilseed rape crop. A high content in the seeds impairs the quality because it restricts the possible use of the cake and the meal in animal nutrition (s. chapter 3.2). On the other hand a low glucosinolate content in the whole plant seems to be one reason for reducing plant resistance to stress and disease (s. chapter 7.3). As glucosinolates play an important role as an intermediary metabolic compounds in S storage the content is linked to the nutritional conditions of the crop environment.

The application of sulphur increases the glucosinolate content. This effect is more distinct, however, in varieties with high glucosinolate concentrations. For 00-varieties which are far lower in glucosinolates only a small response to S is found (Fig. 32). This effect is almost independent of the sulphur supply of the site. On the site with the low as well as with the high S supply the S fertilization leads to the same increase of glucosinolate content (Walker and Booth, 1994). However, site has a far more influential effect on the seed glucosinolate level than S fertilization, particularly for varieties high in glucosinolate.

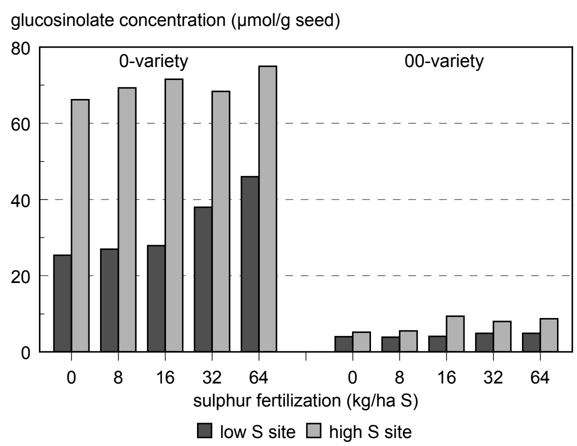

Fig. 32. Effect of sulphur fertilization on the seed glucosinolate content of a 0- and 00-variety of oilseed rape on a low and high sulphur site (Walker and Booth, 1994).

6.2.3. S fertilizer recommendations

... on the basis of soil analysis

Most of sulphur is absorbed from soils by plants in the sulphate form. Therefore, the S availability in the soil depends on the concentration of sulphate in the soil solution. Many methods have been proposed to determine the quantity of plant available sulphate in the soil as a tool to predict sulphur fertilizer requirements. Pot experiments indicate a relatively close relationship between phosphate-extractable-S and plant uptake of sulphur (Scott, 1981). However, in field experiments the phosphate-extractable sulphur was not found to be related to yield response to fertilizer S (Hoque *et al*., 1987).

Recently published results of field experiments from Germany determining yield responses due to sulphur have used as a soil extractant a rather weak (0.0125 n) $CaCl_2$-extraction method parallel to the nitrate determination. Responses to sulphur application were found below a threshold value of 60 kg S_{min}/ha at a soil depth of 0-60 cm (Link, 2000) (Fig. 33).

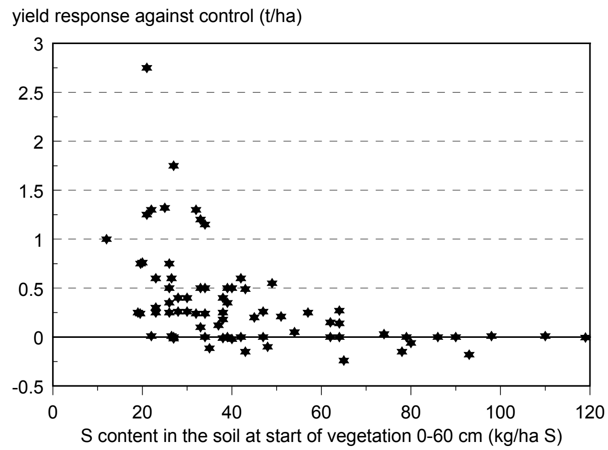

Fig. 33. Yield response of oilseed rape due to S fertilization at different levels of sulphur supply of the soil (Link, 2000).

However, prediction was also not very precise because insufficient account was taken of S release from the soil. Furthermore sulphur input with groundwater during the growth period can be an important source of sulphur and may affect the precision of prediction of the effects of S fertilizer using soil analysis (Bloem, 1998). It seems that only a good knowledge of soil properties and environmental conditions is needed to achieve reasonable S response predictions using results of soil analysis (Syers *et al*., 1987).

... on the basis of plant analysis

Plant analyses are widely used to characterize the sulphur status of rape crops. Many different S fractions and ratios (total S, sulphate S, glutathione, ratio total-

N/total-S, sulphate-S/total-S) have been tested to predict S fertilizer demand (Syers *et al*., 1987; Pinkerton, 1998; Schnug and Haneklaus, 1998; Blake-Kalff *et al*., 2000).

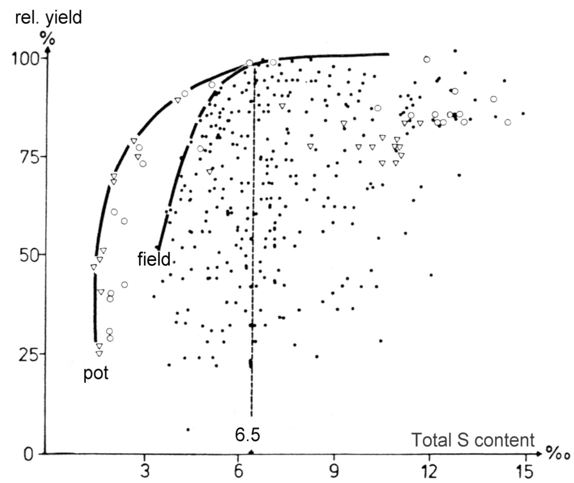

Fig. 34. Yield of winter oilseed rape related to the total S content in younger leaves at the shooting stage (Schnug *et al*., 1984).

Plant analysis data show a comparatively close relationship between total S content in the leaves and yield responses to S application (Schnug *et al*., 1984; Matthey, 2000; Link, 2000). Sulphur contents of fully expanded leaves from the upper plant parts (at stem elongation) above 0.5-0.6% S indicate adequate S status of winter rape varieties in Europe, whereas values below 0.3% S testify to significant S deficiency with high yield responses following S fertilization.

Similar values have been found for spring varieties in Australia (Good and Glendinning, 1998) and mustard varieties in India (Gupta and Dubey, 1998), whereas toria varieties in India showed a critical S level in plant tissue at 0.21% S and a critical N:S ratio of 15:1 (Aulakh and Patel, 1989; reported in Tandon, 1993). In Canada threshold values of 0.2% S at the flowering stage for a low and 0.25% S for a marginal S supply have been reported (Jones, 1986). It can be assumed that these relatively large differences in the critical value depend on the S release of the soils during the vegetative period. In glasshouse experiments in which a constant S supply was maintained during the entire vegetative period a lower critical S level of 0.2% - 0.25% was found (Pinkerton, 1998). The higher threshold values are obtained for high yields and under site conditions where a decline in soil available sulphur has probably occurred.

Additionally the type of plant organ and plant age and the precise stage of development are of crucial importance if the tissue-S-content has to be interpreted in terms of evaluation of the S status of plants. Also, large fluctuations in the S content of both leaves and whole plant may occur (Zhao *et al*., 1993b). It is recommended to sample younger fully expanded leaves because these leaves are the strongest sinks for sulphur and the S concentration of younger leaves is quicly affected by changes in sulphur supply (Schnug and Haneklaus, 1998). Sampling early in the vegetative period (i.e. at the beginning of shooting) allows more time to correct S deficiency by fertilization.

Besides the absolute S content in the leaves the N:S-ratio is also used to determine the S status of rape based on the fact that plants need sulphur like nitrogen mainly for amino acid synthesis. In Canada, a N:S-ratio of 12:1 at the flowering stage was found for maximum rape yield (Bailey, 1986). Higher values lead to reduced yields. Similar ratios of 12:1 for optimum growth have been mentioned for other crops. Other authors have found lower values for rape crops of 9-6:1 (Maynard *et al*., 1983; Janzen and Bettany, 1987; Blake-Kalff *et al*., 2000). However, close relationships between seed yield response and N/S ratio are only found in ranges of extreme N/S ratios.

A further certain disadvantage of the N:S-ratio as a diagnostic criterion is the need for a second nutrient analysis (for N) and the fact that the same N:S-ratio can be obtained at very different concentration levels of both nutrients in the tissues. This has the consequence that a surplus of one nutrient can be misinterpreted as a deficiency of the other. For example a high N:S ratio could result from the oversupply of N even though S is adequate. Conversely, a low N:S ratio suggesting an adequate S supply may be measured when both N and S are actually deficient. It is therefore best to use both the N:S ratio and the absolute total S content to determine whether plants are S deficient (Blake-Kalff *et al*., 2000).

A further disadvantage of leaf analysis is that a result is not available until the later part of vegetative period, the onset of shooting, by which time particularly with severe S deficiency it is often too late for fertilizer treatments to be effective in achieving maximum seed yield.

... on the basis of site characteristics

Another approach to calculate the S fertilizer demand of winter rape in spring has been proposed in Germany which takes into account site characteristics, weather conditions during the winter, cultivation and fertilization in recent years (Zerulla and Pasda, 2000). The principle of this method is that factors influencing S availability in the soil are assessed using a points system with points between 1 and 5. The sum of all the points then provides information as to the likelihood of sulphur deficiency and therefore the possible requirement for sulphur fertilization (Table 20).

Table 20. Assessment of the possible requirement for S fertilization on the basis of site characteristics (Zerulla and Pasda, 2000).

Feature	Evaluation with points		
Soil texture	Sandy soils 1	Loamy soils 3	Clay soils 5
Humus content	Poor < 2 % humus 2	medium 2-4 % humus 3	rich > 4 % humus 4
Available rooting space	shallow 2	high 4	
Damage of soil structure (soil compaction)	Existing 2	Partly existing 3	not existing 4
Nitrate content at start of vegetation in comparison to the long-term average	Below average 1	average 3	Above-average 5
Rainfall October-March in comparison to the long-term average	above-average 1	average 3	below average 5
Cultivation of crops with a high S-demand in the crop rotation	cropping every 3rd year 2	cropping every 4th year 3	cropping every 5th year 4
Crop of this year	Oilseed rape, cabbage or leguminoses 1	Other crops 3	
S deficiency already occured (yield losses, plant analysis, deficiency symptoms)	yes 1	No or unknown 3	
Yield level (t/ha) rape > 3.5[1)] 2.5-3.5[2)] < 2.5[3)] cereal > 7[1)] 5-7[2)] < 5[3)]	high[1)] 2	Medium[2)] 3	low[3)] 4
Intercropping in the last winter	no 2	yes 4	
Use of animal manure	no 1	≤ 1.5 GV/ha 2	> 1.5 GV/ha 3
Considerable use of S containing mineral fertilizers in the last 3 years (single superphosphate, potassium sulfate, ammonium sulfate)	no 1	yes 3	

Evaluation: 19-32 points: probability of S deficiency high → S fertilization necessary
33-40 points: careful observation of crops with high S demand → S fertilization recommended
41-51 points: S deficiency not expected

Additionally other parameters are closely evaluated including previously observed S deficiency and the cultivation of crops with a high sulphur demand, soil structure and weather conditions during the previous vegetation period. Yields, intercropping, humus content and use of animal manure are not so highly assessed because their effect on plant available S is comparatively low.

This approach is not based on a measured procedure but makes it possible at an early stage in the year for the farmers, quickly and cheaply and with sufficient precision, to estimate the need for S-fertilization. This procedure is well accepted by farmers and the extension services in Germany. To use such an approach for other areas, of course means that it must be adapted to the changing conditions influencing S availability.

6.2.4. Time of S application

Because of the very much lower S input from the air and rain, sulphur fertilization is generally recommended for oilseed rape in Northern and Central Europe, in Germany for example at 20-40 kg/ha S (VDLUFA, 2000). On sites with severe deficiency, S fertilizer rates of 50-70 kg/ha S give economic yield responses.

When S deficiency is known to be present, the early application of sulphur in spring is common, at the latest at the start of the vegetative period. A lack of sulphur in the stages of early development reduces yield. Under conditions of severe sulphur stress S fertilization even after the rosette stage does not allow recovery to maximum seed yields and delays plant maturity (Janzen and Bettany, 1984b). S broadcast applications should be completed at the latest before stem elongation. Later applications of S lead to lower seed yields and lower oil contents (Good and Glendinning, 1998) (Fig. 35).

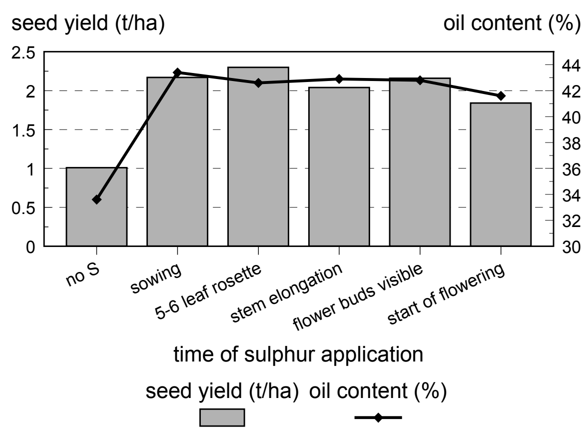

Fig. 35. Effects of time of sulphur application of 40 kg/ha S on seed yield and oil content of oilseed rape (Good and Glendinning, 1998).

In winter varieties, S deficiency can already appear in the autumn. When this occurs, a small application of sulphur of 10-20 kg/ha S should be given before winter although the S demand of rape is relatively low. If elemental S is used as a sulphur source it should be broadcast as far in advance of seeding as possible and worked into the surface soil to encourage oxidation to the plant available sulphate form. An application of elemental sulphur in spring is of little value to the rape crop on severely S deficient soils especially under cold and dry conditions (Noellemeyer *et al*., 1981). Sulphate S is preferential.

6.2.5. Sulphur fertilizers

A variety of different S fertilizers is available, most of them containing sulphur in the sulphate form. Sulphur can only be directly taken up from the soil solution in the form of sulphate that is therefore the most readily plant available S source. In the nitrogen containing S fertilizers the soil acidifying effect of ammonium must be taken into account. Acidification results from the conversion of ammonium to nitrate in the soil. Potassium-, magnesium- or calcium-sulphate are neutral salts and do not alter the soil-pH even after continuous use over several years.

Elemental sulphur cannot be taken up by plants without oxidation to sulphate by thio-bacteria, which is also a soil-pH-reducing process. The oxidation rate depends on the specific surface area and particle size of the elemental sulphur, temperature and soil conditions. The oxidation process is more rapid under warm and damp conditions at low pH and if the particles are small and fine with a high specific area (Jolivet, 1993; Watkinson, 1993; Chapman, 1997; Silva *et al*., 1998).

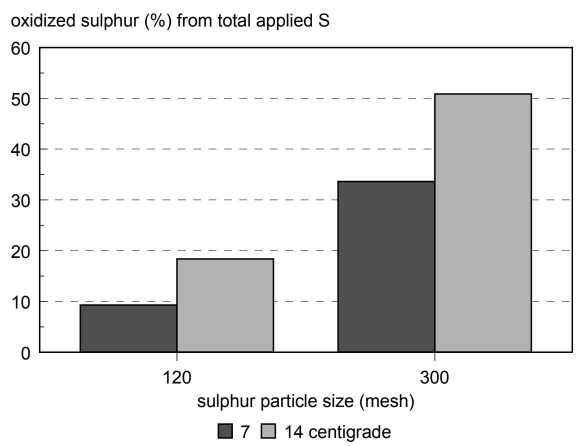

Fig. 36. Oxidation of elemental sulphur of two mesh sizes over 7 weeks as average of four soils (Chapman, 1997).

In Scottish trials on 4 soils, the oxidation rates of elemental sulphur lay between 10% at 7°C and 20% at 14°C with a mesh size of 120 (maximum diameter 124 µm) whereas with a mesh size of 300 (maximum diameter 53 µm) the sulphur oxidation was more rapid with rates of 35% at 7°C and 50% at 14°C over a period of 7 weeks (Fig. 36; Chapman, 1997). In trials from Chile, the oxidation of elemental sulphur to sulphate under dry soil conditions (50% of field capacity) was only about 10% in comparison to wet soil conditions (Silva *et al*., 1998).

These investigations show that the effect of elemental sulphur may be regarded as uncertain in comparison to sulphate-sulphur. Especially in areas with cool and dry periods in the early main growth stages, plant availability of elemental sulphur can be restricted considerably and yields may be depressed because sulphur mobilization is low under such conditions.

The sulphur content of animal manure varies considerably, due to differences in amount and form of dietary ration and to variations in dry matter content. Mean values of about 0.35 kg/m^3 total-S are reported for slurry (i.e. Gutser and Tucher, 2000). However, the plant availability of slurry-sulphur has been found to be low. Total S-uptake of S-deficient spring rape was only significantly affected if sulphur was applied in the form of sulphate. Plant available sulphur in cattle and pig slurry constituted only 5 to 7% of total-sulphur content (Eriksen *et al*., 1995) since most of the sulphur in slurries is found in the form of organic-S and sulfide and not as sulphate. Even in a long-term field experiment with inorganic and organic fertilizers it was concluded that even the residual effect from long-term annual applications of animal manure did not significantly increase the level of plant available soil-sulphur (Erikson and Mortensen, 1999).

6.2.6. Foliar application

Normally, sulphur is applied as solid fertilizer to the soil. However, foliar fertilizer application is also possible and can alleviate yield limitations caused by lack of sulphur (Gransee *et al*., 1999; Matthey, 2000). S foliar fertilization with ammonium- or magnesium-sulphate (Epsom salt) can be immediately effective especially for acute sulphur deficiency where visible deficiency symptoms are present. The main advantage of foliar application lies in the rapid leaf uptake and high availability of the S, which can reduce deficiency symptoms within one week after application. A number of fertilizer trials have revealed the dramatic effects which can be achieved by foliar fertilization with Epsom salt to rape. As an average of 15 sites the yield increased by 0.3 t/ha (Orlovius, 2000). On sites with severe S deficiency the yield response rose to 1.4 t/ha, although a certain additional effects of the Mg may also have played a role. These results have been confirmed by 7-years of Polish trials on sandy loams and medium heavy soils showing yield responses of 0.44 t/ha by foliar fertilization with Epsom salt (Fig. 37; Krauze and Bowszys, 1996).

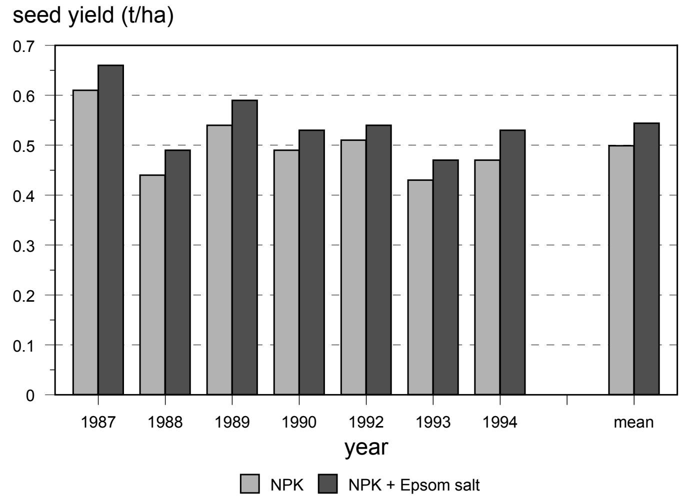

Fig. 37. Effect of a sulphur foliar application in form of Epsom salt on the seed yield of oilseed rape (Krauze and Bowszys, 1996).

Owing to the relatively low S rates of foliar S fertilization (2-5 kg/ha S) such treatments cannot replace soil fertilization. However, foliar applications are suitable for a very rapid correction of sulphur deficiency where deficiency is not recognized until a late stage and where there is a need to cover the high S demand of high yielding rape crop.

6.3. Basal nutrients phosphorus, potassium, magnesium

In comparison to cereal crops the need of oilseed rape for the basal nutrients is high. For this reason, rape very often used to be cultivated following clover-grass or fallow in the rotation, being able to benefit from the higher nutrient supply regenerated by these previous treatments.

Fertilization with the major nutrients P, K, Mg and Ca to high yielding agricultural crops is mostly based on results of soil analyses for available nutrients. The aim is to achieve an optimum nutrient supply in the soil to satisfy the requirement of the rape crop for high yields even during periods of poor nutrient availability as a consequence of periods of drought or other stress factors.

Only when basal nutrients are supplied in adequate amounts is it possible to achieve high efficiency of utilization of the more expensive and ecologically relevant nutrient nitrogen. If the soil nutrient-concentration is optimum, fertilization must be aligned to maintain this status. This is done by replacing those nutrients removed from the soil by the crops taking into account other site factors which influence plant availability of basal nutrients. Using such a strategy it is possible on soils of medium and high CEC to apply phosphate and potassium for several years in advance to supply nutrient quantities to cover the whole crop rotation taking into account that the rape crop is more responsive than cereals.

If the nutrient content of the soil is inadequate, fertilization with basal nutrients must be raised to provide if necessary a long-term build up until an adequate status is achieved. On the other hand when nutrient contents are higher than adequate, rates of fertilizer application can be reduced. Falling nutrient contents in the soil, however, must be monitored by soil analysis and fertilizer application made as appropriate.

6.3.1. Phosphorus

Fertilizer trials in countries throughout the world show under many site conditions that phosphorus is a limiting factor for plant growth (Cramer, 1990; Jain *et al*., 1996; Jaggi and Sharma, 1997; Singh *et al*., 1997b; Gurmani *et al*., 1997; Khattak *et al*., 1996; Grant and Bailey, 1993). Oilseed rape has a higher P demand than cereals or ryegrass. To achieve maximum yield in oilseed rape the content of plant phosphate needs to be a third higher than in wheat (Table 21). This higher P demand of rape is caused by a considerably lower root/shoot ratio compared with wheat or ryegrass (Claasen, 1994).

Table 21. Necessary phosphate content of wheat, ryegrass and winter oilseed rape for 80% of maximum yield (Claasen, 1994).

Crop	P-concentration in soil solution, mmol P/l	P-content in the plant, % P in DM	root/shoot, ratio
wheat	1.2	0.28	16
ryegrass	1.4	0.33	22
rape	**1.4**	**0.39**	**7**

Besides the functions in plant metabolism already described, the nutrient phosphorus supports the development of the root system. The increase in response of root growth to applied phosphorus by rape is much higher than with wheat and flax (Strong and Soper, 1974). A well developed deep root system with many fine roots and root hairs makes it easier for the crop to regenerate after frost damage during winter and facilitates the intensive and effective uptake of all nutrients which is of special importance in periods of stress during growth.

Phosphorus deficiency in rape limits both shoot and root growth. High yields are possible only when the availability of phosphorus in the soil is adequate. In greenhouse pot experiments increasing soil phosphorus supply from 6 to 106 mg/kg P (CAL-extractable) resulted in a significant increase in seed and oil yield and oil concentration (Lickfett *et al*., 1999) (Fig. 38). The P concentration in the seeds and the P accumulation was clearly affected by the P levels in the soil. At maturity most of the phosphorus taken up was present in the seeds which underlines the importance of phosphorus for seed formation. With insufficient P supply, the concentration of phosphorus and phytate in the seeds was lower.

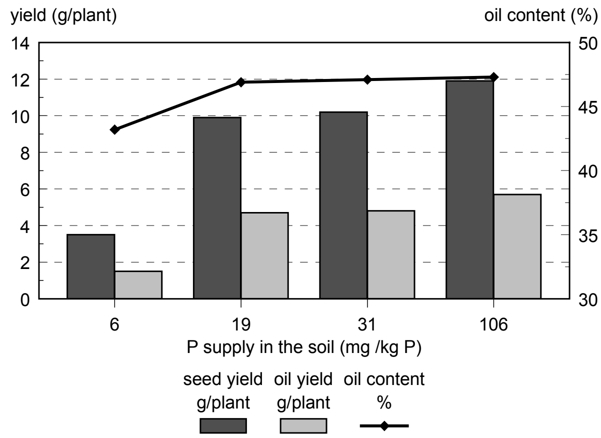

Fig. 38. Seed and oil yield and oil content of oilseed rape as affected by P supply in the soil (Lickfett *et al*., 1999).

The plant phosphorus content relates to extractable soil P supply. From field trials in Czech Republic, 35 mg P/kg soil is indicative of an adequate supply of phosphorus (Kovacik *et al*., 1981). Soper (1971) found a relation between extractable soil phosphorus and yield response due to P fertilization. On Chernozemic soils in Manitoba, oilseed rape did not respond to applied phosphorus where more than 10 mg/kg of $NaHCO_3$- extractable P was present in the soil. Similar values have been found in the USA. On soils with less than 12 mg/kg Olsen-P, P fertilization is advised (Mahler, 1990). In Germany, 45-90 mg/kg soil of lactate-extractable P is recommended as an adequate status (VDLUFA, 1997). With such a target level, P fertilization should be aligned to maintain optimum P status in the soil to compensate for P export from the fields with the seeds (75 kg/ha P_2O_5 for a yield of 3.5 t/ha). In a crop rotation with oilseed rape and cereals, the P demand of the whole crop rotation should be given to the rape crop on soils where P fixation does not present a problem. In Great Britain, an adequate P status of the soil of 16-25 mg/l P (Olsen) is advised combined with a recommendation of 50 kg/ha P_2O_5 (MAFF, 2000).

In India and Pakistan, Indian mustard (*Brassica juncea*) is often cultivated instead of *B. napus* or *B. campestris*. Several authors have confirmed the high P demand of this rape crop, too. Indian mustard shows high yield responses to applied phosphorus, mostly grown on soils of high pH and low in available P. The optimum phosphorus rate lies mostly between 40-60 kg/ha P_2O_5 with yield responses of 0.3-0.7 t/ha (s. Table 22).

Table 22. Results of fertilizer trials with phosphorus to Indian mustard and sarson.

P_2O_5 kg/ha	seed yield t/ha	P_2O_5 kg/ha	seed yield t/ha		P_2O_5 kg/ha	seed yield t/ha	P_2O_5 kg/ha	seed yield t/ha		
			1992	1993				1991	1992	1993
0	1.21	0	0.78	0.84	0	0.89	0	1.26	2.39	3.24
19	1.40	30	0.91	1.03	29	1.21	20	1.29	2.97	3.62
38	1.69	60	1.03	1.13	58	1.62	40	1.61	3.29	3.05
58	1.62						60	1.56	4.08	4.50
mustard clay loam pH 8.2		mustard sandy loam pH 7.8			mustard silty clay loam pH 5.8		sarson loam pH > 7.1			
Jain *et al.* (1996)		Singh *et al.* (1997b)			Jaggi and Sharma (1997)		Gurmani *et al.* (1997)			

However, from the results of Gurmani *et al.* (1997), it can be concluded that especially in years when high yields are obtained even on the control plots, the yield increases due to P fertilization is much higher than in years when yields are limited (s. Fig. 39).

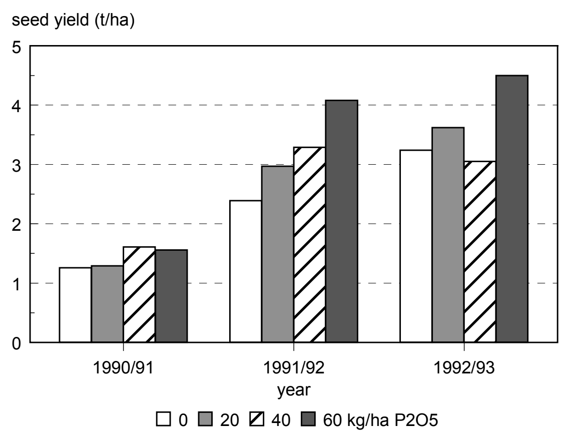

Fig. 39. Effect of different phosphorus fertilizer rates on seed yield of sarson at different yield levels (Gurmani *et al.*, 1997).

For the year with poor growth conditions and a low yield, the yield increase was only 0.35 t/ha with 40 kg/ha P_2O_5 applied, whereas in the years 1992/93 and 1993/94 with better growth conditions, P fertilization gave higher responses of 1.69 t/ha and 1.26 t/ha respectively achieving yields as high as 4.1 to 4.5 t/ha with 60 kg/ha P_2O_5. These findings demonstrate the necessity of ensuring adequate P supply to rape crops especially when yields are high.

6.3.1.1. Interactions

In oilseed rape interactions of phosphorus with other nutrients are not frequently reported. As in other crops, however, they take place and have to be considered in planning fertilization strategy. Jaggi and Sharma (1997) showed a sulphur-phosphorus interaction for Indian mustard on a soil deficient in both sulphur and phosphorus. Lowest seed yields were recorded in the P_0S_0 treatment (Fig. 40). With each increase in P and S levels, seed yields continued to increase. The effect of P and S fertilizer on the seed yield was almost equal at all S- and P-fertilizer levels. However, highest seed yield could only be obtained when both nutrients were supplied the highest rate.

Fig. 40. Interaction of phosphorus and sulphur fertilization on the seed yield of Indian mustard (Jaggi and Sharma, 1997).

The interaction between phosphorus and magnesium was demonstrated in a pot culture experiment with mustard (*Brassica juncea*) (Krishnakumari *et al*., 1999). Without P fertilization, a decreasing trend in seed yields due to Mg application was discernible (Fig. 41). However, the yield response to P fertilization was highest in the treatment with the highest rate of Mg supply. The oil content of mustard corresponded to the effects on yield. The highest oil content was found in the P_2Mg_2 treatments which indicated the positive interaction of P and Mg at higher levels.

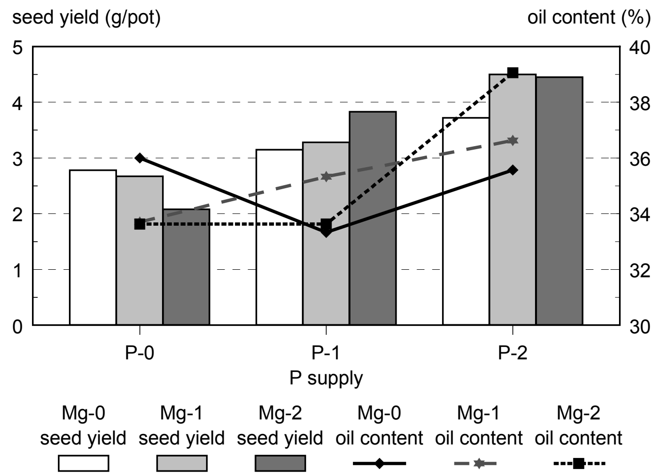

Fig. 41. Effect of different levels of P and Mg supply on seed yield and oil content of mustard (Krishnakumari *et al*., 1999).

6.3.1.2. Quality

Rape quality is mainly genetically determined. Under severe P deficiency conditions oil content decreases (Fig. 38) (Lickfett *et al*., 1999). However, in most field experiments phosphorus supply has only little influence on oil content. Particularly on sites where P application leads to increased protein content the risk of decreased oil content is raised (Bailey and Grant, 1990).

6.3.1.3. P fertilizer recommendations

The big differences between countries in phosphorus fertilizer recommendations are remarkable (s. Table 23). The widely varying application rates can be put down to differences in yield, different site conditions, variations in soil moisture availability and input of other nutrients in relation to balanced crop nutrition. The highest P recommendations are mostly given in those countries where highest yields are achieved (for example France, Germany). In India, the P recommendations are tied to the N application rates because the yield response to P fertilization is only small in the absence of nitrogen but increases markedly if nitrogen is applied. This again demonstrates the value and necessity of balanced fertilization with all nutrients.

Table 23. Phosphorus fertilizer recommendations to oilseed rape in different countries at an adequate P status of the soil.

	kg P_2O_5/ha	
Germany	70 – 100	CA Hannover (1998)
Great Britain	50	MAFF (2000)
Canada	20 – 30	Grant and Bailey (1993)
USA	45	Mahler (1990)
France	60 on soils pH 5.5 – 7.5 80 on soils pH > 7.5 150 on soils pH < 5.5	Merrien (1992)
India	0 – 40 dryland mustard 30 – 40 rainfed mustard	Tandon (1993)

On non-calcareous soils and on soils well supplied with P, the time of P application is not too important, because the plants take up most of the phosphorus from the soil and less directly from fertilizer P. If the soil is tilled, an application before soil cultivation can be advantageous because it results in a more even distribution within the whole topsoil and for this reason has a higher availability. However, on calcareous soils and soils of high pH (> 7) as well as on soils with a high P fixation capacity, an application in autumn may lead to conversion to less soluble forms and therefore decreases the P availability with time. On such sites a spring P application may improve fertilizer efficiency.

Phosphorus fertilizers are frequently applied broadcast to the soil. From the Canadian prairies it has been reported that P placement in narrow bands 8-10 cm below the soil surface and close to the seeds or beside the row can increase yield responses and leads to higher yields (Bailey and Grant, 1990). However, rape can react sensitively to placement of P fertilizers. This is especially so in dry years when plant emergence was reduced by one-third. It was therefore concluded that maximum yield can only be obtained on such soils if the fertilizer is placed away from the seeds and not too close to the row. Bailey and Grant (1990) observed yield advantages through P banding 2.5 cm below and to the side of the seed compared with broadcast and incorporated application.

6.3.1.4. Phosphorus fertilizers

The various phosphate fertilizers differ in chemical composition and P solubility. Water-soluble P fertilizers like super- and triplesuperphosphate, mono- and diammoniumphosphate, sinter phosphate and basic slags from the steel industry have a high P solubility and are suitable for most soil types. In hard crystalline apatites especially phosphate is nearly insoluble.

The P availability of softer rock phosphates depends on specific site conditions, the content of soluble phosphate in the soil, the soil pH and the crop efficiency in rock phosphate exploitation. The Brassica species mustard, rape or cabbage are highly efficient in the use of soft rock phosphate in comparison to cereals (Mengel and Kirkby, 2001). Particularly on acid soils with a pH value below 5 the efficiency of rock phosphates is similar to water soluble P fertilizers (Mengel, 1991). However, on neutral or alkaline soils the P exploitation from rock phosphates is rather low.

6.3.2. Potassium

Oilseed rape has a high potassium demand. The K uptake of winter rape lies between 200 and 400 kg/ha K_2O although the concentration in the seeds is comparatively low with values of 0.9-1.0% K in dry matter. Thus there is a considerable difference between the K uptake of rape and K removal from the field with the seeds if the straw is not harvested but remains on the field. Although the potassium export with the seeds from the field is low at about 30-60 kg/ha K_2O, growth is severely restricted by insufficient K supply. Soper (1971) found a relationship between the extractable K content in the soil and the yield response to K fertilization. To obtain maximum yields, a K supply in the soil of 150-200 ppm ammonium acetate extractable K was necessary. Similar values are recommended for an ammonium nitrate extraction in the UK (MAFF, 2000) and for lactate acetate extraction in Germany (VDLUFA, 1999).

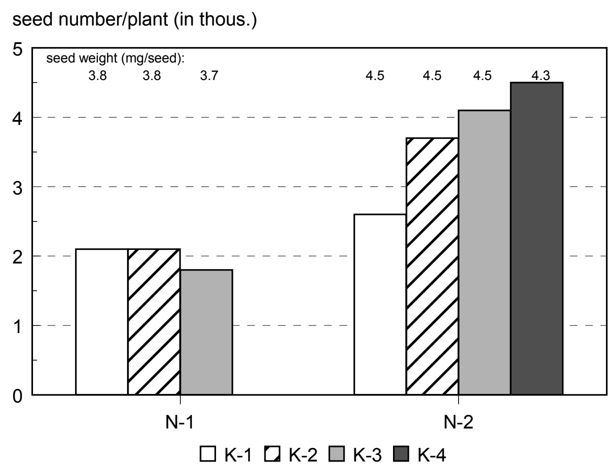

Fig. 42. Influence of potassium on the seed weight and the seed number per plant of oilseed rape at different nitrogen supply (Forster, 1978).

Pot experiments indicate that potassium increases seed number per plant particularly with intensive nitrogen fertilization (Fig. 42), whereas seed weight is unaffected (Forster, 1978). In field experiments such relationships are often not so clear, because a number of other site factors influence the availability of K to the plants. Only on soils with severe potassium deficiency are such effects reported with an increased number of seeds per plant as a consequence of an increased number of pods per plant and not because of an increased number of seeds per pod (Holmes, 1980).

In the older literature, there are some reports that despite the high K uptake of oilseed rape, yield responses due to K fertilization are comparatively low (drawn up by Grant and Bailey, 1993). However, these observations refer to fertilizer experiments with comparatively low yields of between 1 and 2 t/ha where it can be assumed that production intensity is low and that nutrient demand is not very great. Fertilizer trials in recent years in Germany with yields above 4 t/ha show considerable yield increases due to potassium fertilization. In these field trials on loamy soils with 00-varieties, yield responses of 7-10% were obtained by increasing rates of K supply (Fig. 43).

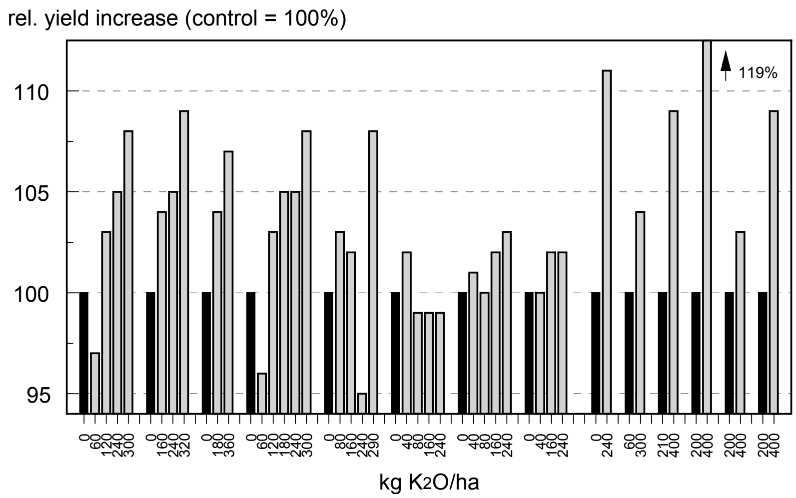

Fig. 43. Effect of K fertilization on seed yield of oilseed rape on 14 different sites in Germany with a yield level above 4 t/ha (Orlovius, 2000).

For such elevated yields, there is particularly high demand for K during the most intensive growth stages from shooting onwards until flowering. A potassium uptake of about 10 kg/ha/day K_2O must be maintained, otherwise optimum growth and yield formation are disturbed. Also in high yielding K fertilizer trials with mustard on K deficient soils significant yield responses were obtained with increasing rates of K (Singh *et al.*, 1997c; Mondal *et al.*, 1997; Rao and Rao, 1996).

6.3.2.1. Quality

6.3.2.1.1. Oil content

Potassium plays a role in the enzyme systems controlling photosynthesis metabolism and the conversion of assimilates to oil within fat metabolism. This K effect can be clearly observed in pot experiments with winter-rape varieties (Forster, 1977). In a pot trial using a sandy soil poor in potassium, increasing rates of K raised the oil content by 1.5% (absolute) with an adequate N supply whereas this effect was almost negligible in plants which were slightly N deficient (Fig. 45). Thus by improving K supply, quality was enhanced which together with the beneficial yield response resulted in an increased oil yield, the most important criterion in the cultivation of oilseed rape.

However, a summarizing report of Holmes (1980) citing several field trials from different countries pointed out that an increase in oil content resulting from addition of K occurred on only one site and that with severe K deficiency. Possibly this seemingly lack of effect of K can be attributed to a low N input and a varietal influence. In field trials in China with 180 kg/ha N on three different paddy soils low in potassium, increasing K rates from 0 until 180 kg/ha K_2O raised the oil content of oilseed rape by an absolute amount of 4% (Fig. 44; Yousheng *et al.*, 1991).

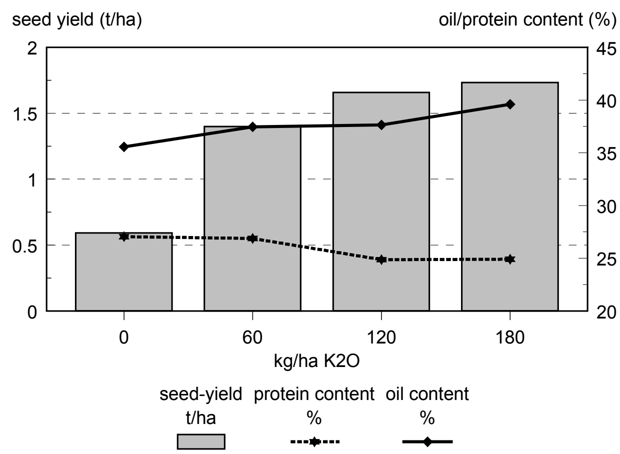

Fig. 44. Effect of increasing potassium fertilization on seed yield, oil and protein content of oilseed rape (Yousheng *et al.*, 1991).

Similar results were obtained in field trials from India with mustard on a sandy loam where the application of potassium significantly increased the oil percentage of seeds by 4.1% (absolute) with raising K rates up to 180 kg/ha K_2O (Singh *et al.*, 1997c). These experiments tested the two K sources potassium chloride and potassium sulphate. In both years, potassium sulphate proved superior to potassium chloride probably because of the improved sulphur supply with potassium sulphate (s. Table 25).

6.3.2.1.2. Protein content

There is little information from field experiments as to the influence of potassium on the protein content of rapeseeds. In these publications almost no effect of K has been found (Holmes, 1980). However, in pot experiments an inverse correlation between protein and oil content was reported. In the investigations of Forster (1977) already mentioned the beneficial effect of K on oil content led to a decreasing protein content at the high N level, whereas with a low N supply the increasing K rates slightly decreased the oil content but raised the protein content of the rapeseeds.

These results have been confirmed by field trials in China (Yousheng *et al.*, 1991). At a nitrogen level of 180 kg N /ha, increasing K rates of fertilizer led to a decreasing protein content whereas oil content was enhanced by 1.9-4.0% when K was applied up to 180 kg/ha K_2O (Fig. 44).

6.3.2.2. Interactions

Interactions with other nutrients may influence the yield response due to potassium fertilization as shown in pot experiments with nitrogen (Forster, 1977). At sub-optimal N supply increasing K rates did not affect seed yield but with optimal N rates the plants benefited from a higher K dressing, seed yield increasing to the highest K rate (Fig. 45).

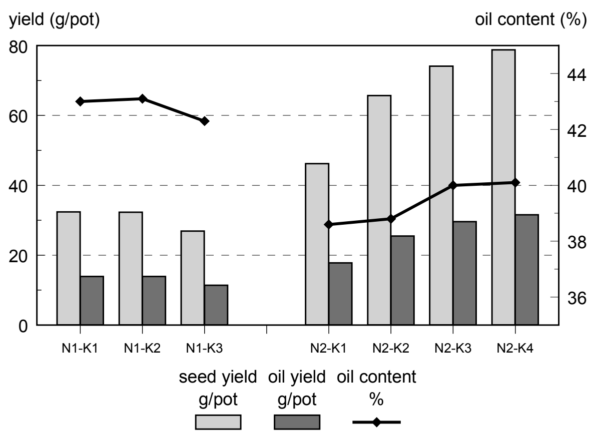

Fig. 45. Interaction of potassium and nitrogen on seed yield, oil yield and oil content of oilseed rape (pot trials; Forster, 1977).

The increased N supply lowered the oil content of the seeds. However, this negative effect of N was lessened by the enhanced K application. The decrease in oil content due to raising N fertilization was 4.4% in the K1 treatment, but only 2.3% (absolute) at the K3 level in varieties low in erucic acid. Increasing K supply on the N2 treatments raised the oil content from K1 to K4 by 1.5% (absolute). Since seed yields also increased considerably, potassium nutrition had a beneficial effect on oil production. Similar results have been obtained from field trials in France (SCPA, 1974).

6.3.2.3. K fertilizer recommendations

Taking into account the results of fertilizer experiments together with the fertilizing approach already mentioned of giving required K rates to maintain the optimum content of exchangeable K in the soil (s. chapter 6.3), it is recommended that the full needs of K for the entire crop rotation should be applied in advance of the rape crop. Using such a strategy K uptake requirements of rape are satisfied and yield limitation due to lack of potassium is avoided. Employing this strategy, yield responses of 0.2 t/ha have been reported in several fertilizer trials in Germany (Orlovius, 1984). Because the straw mostly remains on the fields, the following crop benefits from the large amounts of potash that it contains. This fertilizing strategy also allows farmers to save time by making only one potassium application within the crop rotation instead of yearly applications.

However, rotational K fertilizer application is inappropriate for sandy and organic soils because of the increased risk of K leaching. On such soils therefore, K fertilization must be adjusted to the yearly demand of each crop. For oilseed rape the main application of K fertilizers should made in spring before the beginning of the growth period. On light soils of low K status about a quarter of the total K rate should already be applied in autumn because rape takes up 50-100 kg/ha K_2O before winter (for winter types). On such soils because of K leaching it can not be assumed that the total amount of potassium in the crop residues can be utilized by the following crop.

On medium and heavy soils the time of K application is not of great importance particularly on soils with an adequate or high K status. It is generally accepted that K fertilizers are best broadcast onto the soil. Incorporation of K fertilizers into the soil is mostly of advantage because of the more even distribution of potassium within the topsoil which can also enhance availability under temporary drought periods during growth.

It has been reported from Canada that potash banding below and to the side of the seed row is more effective than broadcast application (Grant and Baily, 1993). However, placement too near the seed must be avoided because of increasing the risk of damage to the germinating seedlings as a consequence of the high osmotic pressure associated with potassium chloride.

On soils fixing K (mostly combined with a low exchangeable K supply in the soil) the total K rate should be divided into one-third in autumn and two-thirds in spring, to satisfy the relatively high K-demand of winter-rape before winter and to avoid a fixation of the applied potassium by the clay minerals.

Potassium recommendations vary considerably between countries depending on yield, rape species and variety, as well as on soil moisture conditions (Table 24). In countries in which yields are generally poor, K fertilizer recommendations are also low whereas in countries in which high yields are attained like France or Germany higher K rates are advised.

Table 24. Potassium fertilizer recommendations to oilseed rape in different countries at an adequate K status of the soil.

	kg K_2O/ha	
Germany	140 – 200	CA Hannover (1998)
Great Britain	40	MAFF (2000)
Canada	60	Grant & Bailey (1993)
USA	only responses on soils < 100 ppm K	Mahler (1990)
France	70 on soils with high K availability 135 on soils with medium K availability 225 on soils with poor K availability	Merrien (1990)
India	0 – 20 dryland mustard 20 rainfed mustard	Tandon (1993)

6.3.2.4. K fertilizers

The most frequently used K fertilizer for oilseed rape is potassium chloride or muriate of potash (MOP) with a concentration between 40 and 60% K_2O either as straight or in compound fertilizers. The lower grades of K straights beside potash additionally contain magnesium, sulphur, and/or sodium. When simultaneously to the demand for potash there is also a demand for sulphur or magnesium by oilseed rape potassium sulphate (SOP 50% K_2O, 18% S) or potassium magnesium sulphate (30% K_2O, 17% S, 10% MgO) are used and improve yield and quality, as shown in trials with Indian mustard (Singh *et al.*, 1997c). In both experimental years the use of SOP led to a small yield response but to a significant increase of the oil content (Table 25). In France a yield response of 0.3 t/ha was obtained as a result of sulphur addition with a top dressing of SOP of 100 kg/ha K_2O (Fauconnier, 1983). In these named fertilizers all nutrients are contained in a water soluble, readily plant available and quick-acting form.

Table 25. Effect of sources of potassium on seed yield and oil content of mustard (Singh *et al*., 1997c).

K-source	seed yield t/ha		oil content (%)	
	1990/91	1991/92	1990/91	1991/92
KCL	2.30	2.36	35.6	36.0
K_2SO_4	2.34	2.40	36.4	38.7

6.3.3. Magnesium

The magnesium demand of rape is often underestimated. The bulk of Mg is taken up during the four weeks from shooting until flowering. Therefore substantial demands are made on the availability of Mg to meet this high short-term requirement. Magnesium deficiency can be caused by either a low Mg content of the soil, and low plant availability of Mg sources, or by a supression of Mg uptake by cation antagonism, especially with wide ratios of Ca:Mg, NH_4:Mg, or K:Mg.

Magnesium deficiency occurs especially on diluvial acid sandy soils or on weathered acid rock soils low in CEC because of their poor Mg content. On coarse textured sandy soils in areas of high precipitation, the risk of Mg loss by leaching is increased. Mg deficiency symptoms are also observed on some calcareous soils. Where pure calcitic limestones weather, maintainance of an adequate Mg supply to plants is doublly at risk because of the low Mg content of the soil parent material and additionally, uptake competition at the root surface with calcium. The same mechanism involving Ca/Mg-antagonism takes place on acid and neutral soils after high rates of application of calcitic lime. High fertilization with other cations like NH_4^+ or K^+ may also induce magnesium shortage. Ensuring the adequate nutrition of a crop with magnesium is a good example which shows particularly clearly the necessity for a balanced fertilization with all nutrients.

The probability of a response to Mg fertilization increases the more of the following factors are present:

- low Mg content of the soil
- high pH of the soil (Ca/Mg antagonism)
- liming with Mg free liming material (Ca/Mg antagonism)
- N fertilization in the NH_4 form (also slurry) (NH_4/Mg antagonism)
- compacted stagnant soils
- during cold and wet growth conditions in the vegetative period
- during drought periods
- under intensive crop cultivation in which high yields are attained

Many Mg fertilizer trials particularly in high yielding areas show a response to magnesium fertilization, which is not always related solely to the exchangeable Mg content of the soil (Fig. 46). Despite the adequate Mg status of the soil, Mg fertilization led to considerable seed yield increases of 0.46 and 0.6 t/ha. The soils were of high pH on both sites and therefore the presence of a Ca/Mg uptake antagonism may be supposed.

Because soils originate from different geological formations and develop under different conditions, Mg requirement is strongly site dependent. Yield responses of 0.2 t/ha seeds were obtained on average from 25 field trials carried out in typical rape areas of Germany, mostly on acid sandy and loamy soils to which 50 kg/ha MgO was supplied in the form of Kieserite (Orlovius, 2000). However, the range of the yield responses lay between 0 and 1.95 t/ha and did not depend on the exchangeable Mg content of the topsoil. Probably the Mg content of the subsoils differed significantly and influenced the effect of fertilization.

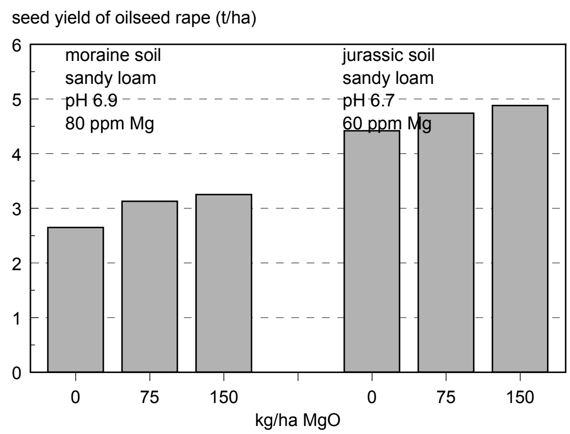

Fig. 46. Effect of a Mg fertilization on the seed yield of oilseed rape on two soils of high pH.

Cermak *et al*. (2000) found similar yield responses in the Czech Republic of about 0.2 t/ha after an application of 24 kg/ha MgO as an average of 9 fertilizer trials over three years. Considerable yield increases of 45% have been recorded in mustard on alluvial soils of Uttar Pradesh in India (Tandon, 1989).

6.3.3.1. Interactions

In pot experiments with Indian mustard (*Brassica juncea*) the importance of balanced fertilization is demonstrated with the nutrients magnesium and sulphur (Purakayastha and Nad, 1998). It is shown that the application of single nutrients either magnesium or sulphur is not so effective as when of magnesium and sulphur are applied together (Fig. 47). At the S_0 level Mg fertilization increased seed yields by 4.7%. However, at the S_2 level the yield increment was 8.4% due to the Mg application.

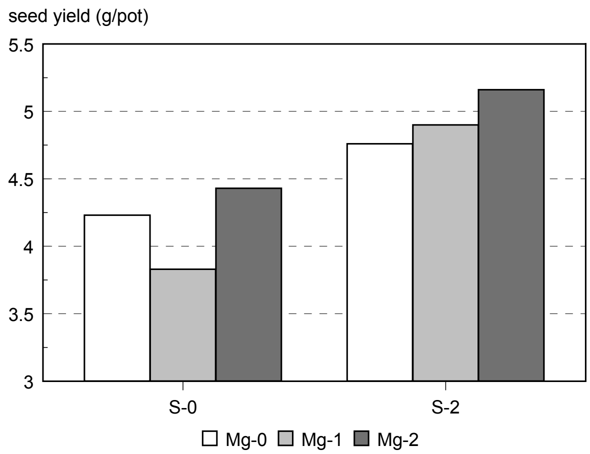

Fig. 47. Effect of increasing magnesium fertilization on seed yield of mustard at different levels of sulphur supply (Purakayastha and Nad, 1998).

On an alluvial soil with 57 ppm available Mg, the oil content of *Brassica juncea* was substantially increased (by +7.7%) as the result of Mg application at a rate of 40 kg/ha Mg (Singh and Singh, 1978). A positive interaction between sulphur and magnesium was observed with highest oil content being achieved by fertilizing with both Mg and S (Fig. 48).

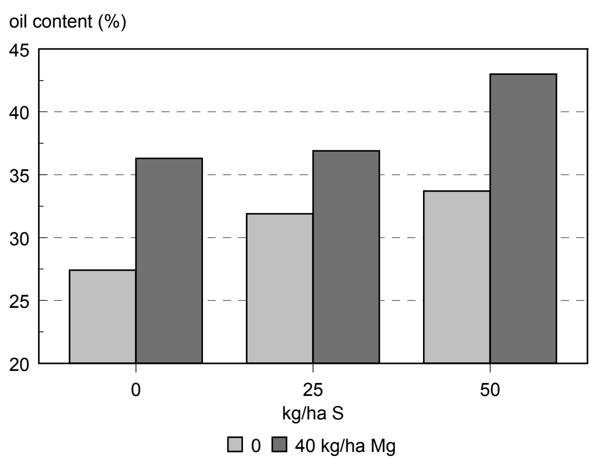

Fig. 48. Interaction of magnesium and sulphur fertilization on the oil content of mustard (Singh and Singh, 1978).

6.3.3.2. Mg fertilizer recommendations

In high yielding areas especially, where inputs are high, it is essential to achieve a balanced fertilization between all nutrients. The presence of high concentrations of K^+, NH_4^+ or Ca^{2+} or combinations of these ions restricts magnesium uptake. In acid soils, it is supposed that Al depresses Mg uptake (Grimme, 1983). The availability of Mg to plants therefore does not only depend on the Mg supply in the soil but also on additional soil and site conditions for which there is no indication from soil analysis for Mg.

Nevertheless an adequate Mg status of the soil is important to ensure the satisfactory uptake of Mg by rape plants particularly at times of intensive demand. This is characterized by the state advisory board in Germany as shown in Table 26 depending on the clay content. To avoid a K/Mg antagonism the ratio of extractable K:Mg in the soil should not exceed 3:1. For Indian conditions, Tandon (1989) cited as critical Mg levels in the soil 1 me Mg/100 g soil (ammonium acetate extraction) or 4% of the CEC.

Table 26. Extractable Mg content of the soil for an adequate Mg status (CA Hannover, 1998).

Soil	mg Mg/kg soil*
light	30- 70
middle	60- 90
heavy	90-120

* extracted with $CaCl_2$-method after Schachtschabel (1954).

Where there is adequate Mg in the soil, the Mg export from the field with the seeds has to be replaced to maintain the Mg content of the soil, this Mg demand amounting to 10 kg MgO/t seed. Depending on the geological parent material of the soil and the rainfall, Mg leaching at a rate of about 30-80 kg MgO/ha/year must be considered. Recommendations lie between 30 and 45 kg MgO/ha (Germany) for a 4 t/ha yield. On soils with a high potassium content, Mg fertilizer recommendations are increased by 10-20 kg /ha MgO. Mg fertilizer recommendations are similar in other European countries.

6.3.3.3. Magnesium fertilizers

The most important magnesium fertilizers are Mg carbonates in the form of dolomite and Mg limestone and Mg sulphate in the form of Kieserite. Mg carbonates are used for acid soils which need to be limed regularly, and are often applied together with Mg sulphate to obtain a rapid response. It is appropriate to raise the soil magnesium content to cover peak Mg demand and maintain the level in the long-term. The effect of Mg carbonates is long lasting. Because of the high rates of limestone commonly used (up to 20 t/ha) the magnesium dressings with these fertilizers are often high (130-340 kg/ha MgO), and their effect is to release Mg slowly into the soil. Magnesium carbonates are particularly useful for acid soils as they act simultaneously to raise soil pH.

Unlike these basic materials, Kieserite dissolves quickly and independently of soil pH. Its high Mg content (25-27% MgO) and high solubility makes it an efficient fertilizer even when applied at low rates (30-60 kg/ha MgO). Kieserite increases the Mg concentration in the soil solution and raises the exchangeable Mg content immediately. The advantage of its use is a quick response under all site conditions, even on a soil at pH above 6.5.

In soils of high pH values and/or containing free calcium carbonate the solubility of Mg carbonates is very low and Mg sulphate should be the magnesium fertilizer of choice. Mg-carbonates are not used on such soils because of increasing risk of depressing the availability of trace elements and inducing deficiencies. Owing to the high solubility of Mg sulphate even under alkaline conditions Kieserite exerts an immediate influence in reducing competition for uptake at the root surface between calcium and magnesium as well as between magnesium and potassium. Furthermore it contributes to sulphur nutrition of the rape crop because of its sulphur content. Andres (1992) presented a model for the effective use of Kieserite and Mg-carbonates in agriculture (Fig. 49).

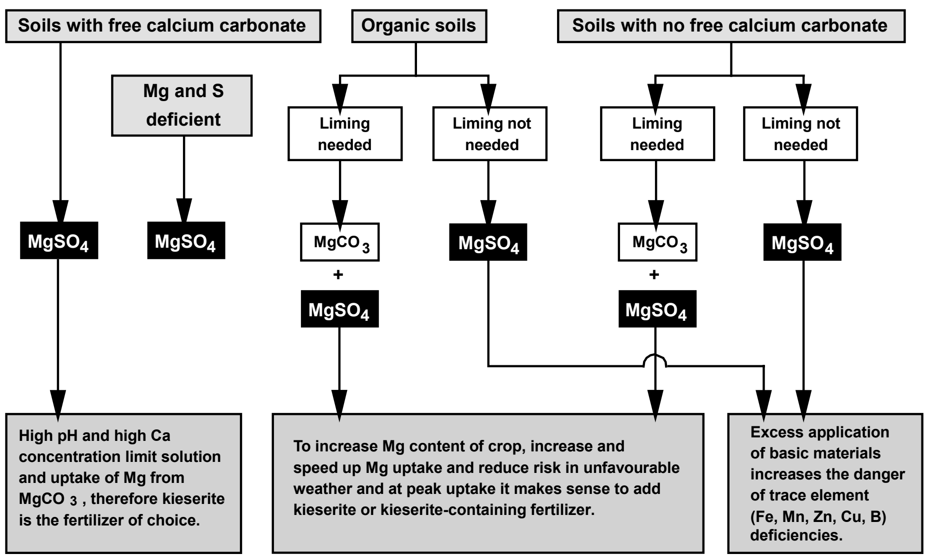

Fig. 49. Agrochemical conditions for the use of Mg carbonate and Mg sulphate in agriculture (Andres, 1992).

6.3.3.4. Foliar fertilization

In high yielding leafy crops in particular, yield responses can result from foliar fertilization with magnesium if the nutrient supply is temporarily insufficient for optimum production. Such critical periods can arise as a result of either, temporary unavailability of soil Mg or because nutrient uptake by the roots is depressed during transition from the vegetative to reproductive and storage phases. When this occurs, foliar spraying with Mg solutions has proved to be an effective means of alleviating these nutrient limitations and satisfying the high short-term nutrient demands of rape, even under conditions of adequate soil fertility.

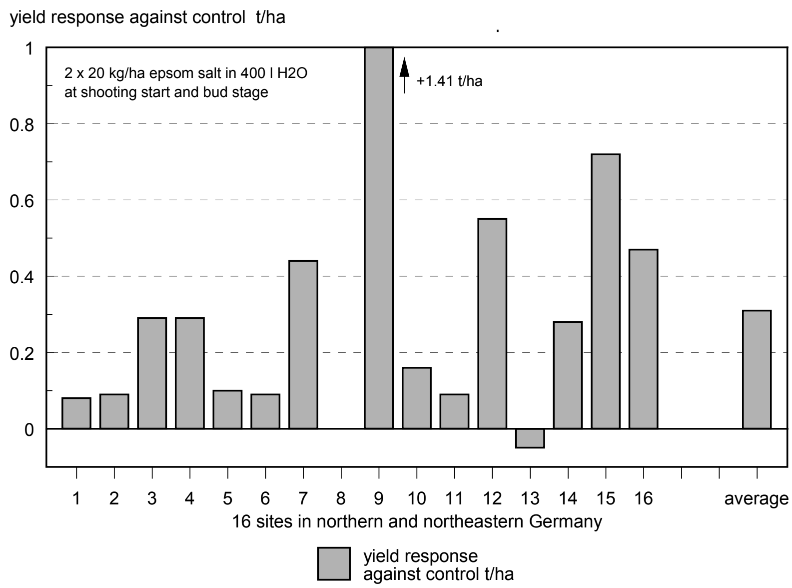

Fig. 50. Effect of two Mg foliar applications of each 20 kg/ha Epsom salt on the seed yield of oil seed rape on 16 fertilizer trials in Germany (Orlovius, 2000).

The foliar fertilizers used are Mg chelates and Epsom Salt ($MgSO_4 \cdot 7H_2O$), the latter having the advantage of an additional sulphur content of 13% S. Fertilizer trials in Germany with foliar spraying of Epsom Salt (2 x 20 kg/ha in 400 l water = 2 x 3.2 kg/ha MgO) show yield responses of up to 1.4 t/ha depending on site conditions and in some cases partly to sulphur deficiency (Fig. 50). Together with these yield responses oil content was considerably improved by 0.5-1.0% (Orlovius, 2000). Similar yield responses by foliar application with Epsom salt have been obtained in Poland (Krauze and Bowszys, 1996) and in the Czech Republic (Cermak *et al*., 2000).

6.3.4. Calcium

Absolute calcium deficiency is rarely observed in rape crops, although Ca uptake is comparatively high at 150-200 kg/ha CaO. Under most conditions the Ca concentration in the soil solution is high enough to cover the calcium demand of the rape plants. However, achieving high yielding rape crops is highly dependent on soil pH. Taking into account soil texture the pH should be as high as possible. For high yielding rape crops therefore, liming treatments are very important to adjust and to maintain optimum soil structure, tilth and crumb stability for best growing conditions.

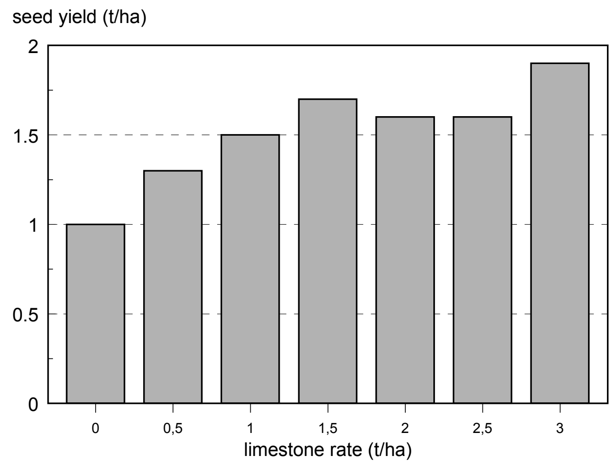

Fig. 51. The influence of increasing rates of limestone on seed yield of winter rape (Mineikiene, 1998).

Without liming, soil pH falls due to natural acidification and Ca leaching. The main purpose of liming acid soils is to decrease soluble aluminium by precipitation and to enhance plant availability of phosphate and other nutrients. In field trials in Lithuania (Fig. 51) on acid soils with a soil pH below 4.5 the application of 1.5 t/ha led to a significant yield response 0.7 t/ha as an average over three years (Mineikiene, 1998).

The most important lime fertilizers are limestone ($CaCO_3$) and dolomite. They act comparatively slowly and are more recommended for lighter soils. Calcination of lime yields burnt lime (CaO), the most immediate and effective form which is particularly recommended for loamy and clayey soils. Many liming materials also contain magnesium due to the Mg content of the rock limestone or dolomite and these are especially used on Mg deficient acid soils. Besides these lime products from natural sources there also liming materials from industrial processes, for example converter lime or basic slag as byproducts of the steel industry or waste products from refining of beet sugar. These are also mainly Ca carbonates.

On salt affected soils characterized by neutral or alkaline soil reaction, calcium nevertheless is needed for amending soil structure. With the application of neutral calcium salts (mostly gypsum) adsorbed sodium can be replaced by Ca to floccate soil colloids (Mengel and Kirkby, 2001).

From practical farming report it is known that liming depresses the incidence of the finger- and toe-disease. After the application of 1-1.5 t/ha burnt lime incorporated in the top soil close to the soil surface the appearance of this disease was considerably reduced due to a temporarily extreme pH-increase in the root-zone of the young rape plants (Cramer, 1990).

6.4. Micronutrients

Acute micronutrient deficiencies in rape crops with visible symptoms appear relatively rarely on most soils. However, on specific soils or under specific conditions, micronutrient deficiency may considerably limit crop production and seed yield. Additionally latent deficiency in which there are no visible symptoms but which is also yield restricting has a wider distribution. Soil and plant analysis is required to recognize latent deficiency so that fertilizer recommendations can be made. However, relationships between soil or plant analysis data and yield response due to micronutrient fertilization are often imprecise. Foliar feeding with micronutrients is particularly recommended as a prophylactic treatment to allow for possible interruptions of nutrient uptake from the soil via roots. Many different single – or multi – micronutrient fertilizers are available.

6.4.1. Boron

Rape crops are included in those species which are characterized as being most sensitive to boron deficiency and most responsive to boron application (Bergmann, 1992; Shorrocks, 1997). Moreover, rape crops are often cultivated on soils low in B (strongly weathered soils, course textured soils, shallow soils, thin soils over calcareous soils, volcanic ash soils) or where plant availability of boron is reduced, for example as a consequence of high soil pH, liming and/or drought periods during the growth period. For this reason boron deficiency in rape crops is observed on a worldwide basis (Shorrocks, 1997). Oilseed rape gives a yield response to B fertilization which corresponds to the extractable B content of the soil (Table 27).

Table 27. Effect of B fertilization on the yield response of oilseed rape on sites with different hot water extractable B content in the soil (Buchner and Sturm, 1985).

Site	B content in the soil ppm	Yield responses to B fertilization t/ha
1	0.44	0.52
2	0.58	0.12
3	0.58	0.13
4	0.74	0.05

Lack of boron can be the reason for sterility in rape crops as was reported in Canada (Nyborg and Hoyt, 1970; Nuttal *et al*., 1987) and China (Xu, 1988). Pollen germination especially as well as pollen tube growth and floral abortion are affected (Zaman *et al*., 1998). Under boron deficiency pod set per plant and seed number per pod are reduced which leads to a significant drop in seed yields (Fig. 52).

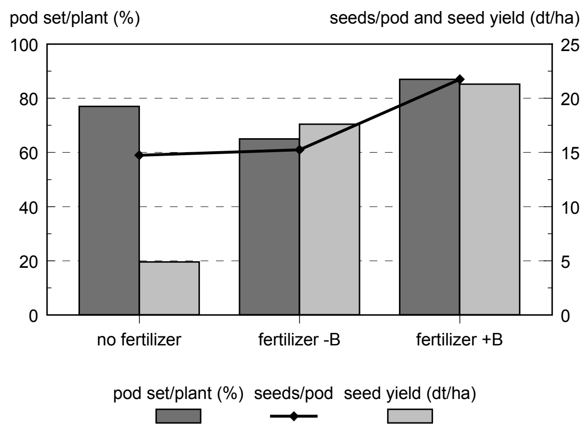

Fig. 52. Influence of boron in combating sterility and on seed yield of oilseed rape (Zaman *et al*., 1998).

Xue *et al*. (1998) identified differences in B efficiency between *Brassica napus* varieties with significant differences in leaf B concentration at the same site. However, B efficiency was not related to the quality of oilseed rape cultivars (00 / conventional). In both groups, varieties were found with high as well as with low B efficiency. Although there was not a very close relationship between B content in the leaves and yield response due to B fertilization, it could be concluded in these investigations on B deficient soils that a B content of 25-30 ppm B in the leaves was necessary to achieve maximum seed yield (Fig. 53).

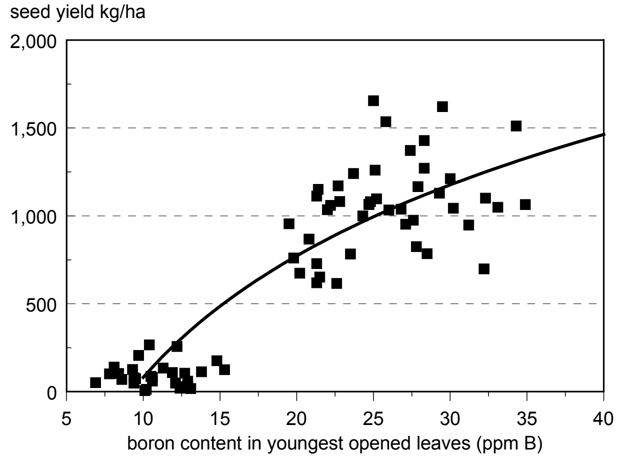

Fig. 53. Relation between the boron content in the youngest opened leaves and the seed yield of oilseed rape (Xue *et al*., 1998).

Similar values were found in Pakistan on B deficient alkaline calcareous soils with 32 ppm B in whole shoots and 38 ppm B in most recently matured leaves (Rashid *et al*., 1994). In these experiments, mustard showed a higher critical tissue B level with 49 ppm B in the leaves and a higher B fertilizer demand to achieve optimum seed yield than *Brassica napus*.

6.4.1.1. Interactions

Although measurements of the hot water extractable B in the soil can be closely related to B concentrations in leaves and the total uptake of plants especially in pot experiments (Rashid *et al*., 1994), boron availability and yield responses to B fertilization in field experiments are additionally influenced by other site conditions which can not be accounted for by soil analysis.

Interactions with other nutrients must also be considered which influence B availability and the effect of fertilizer treatments. Results from Australia suggest that an adequate Zn supply helps to ameliorate the detrimental effects of low B supply (Grewal *et al*., 1998). The findings furthermore indicate that varieties differ in tolerance to B deficiency in relation to Zn supply. Increasing the Zn supply from adequate to excess level at low B supply increased the B content of the leaves and enhanced biomass and seed yield of mustard (Sinha *et al*., 2000). However, at an adequate or excess B supply the excess Zn had the opposite effect (Fig. 54) and decreased yields of biomass and seeds. The highest seed yields were achieved when both Zn and B were adequately supplied.

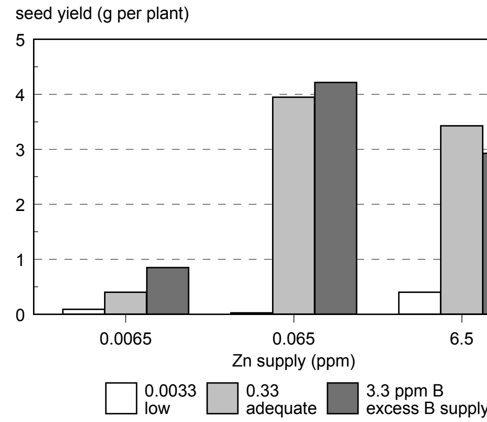

Fig. 54. Seed yield of mustard as influenced by boron-zinc interaction (Sinha *et al*., 2000).

A significant interaction between boron and potassium on the yield of oilseed rape has been reported in China (Yousheng *et al*., 1991). K application without B fertilization to soils extremely deficient in B led to severe B deficiency symptoms and was without effect on seed yield. However, on the plots supplied with B, application of K resulted in a yield increase of 0.4 t/ha. On the other hand, the effectiveness of the boron fertilization was considerably enhanced by the raised K supply (Fig. 55). Potassium was able to play a beneficial role on seed yields only when boron nutrition was satisfactory and *vice versa*.

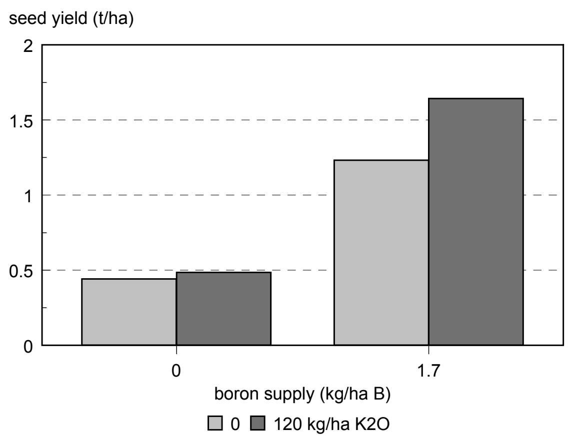

Fig. 55. Interaction of boron and potasssium fertilization on the seed yield of oilseed rape (Yousheng *et al*., 1991).

6.4.1.2. B fertilizer recommendations

The hot water extraction method is an often used as a soil testing method to predict the necessity of B fertilization. The critical value depends on soil characteristics. With increasing clay content the critical level for adequate B content of the soil also rises (Table 28).

Table 28. Hot water extractable contents of boron for adequate B-status of the soil in relation to texture (CA Hannover, 1998).

Soil texture →	Sandy soils	Loamy sands, sandy loams, loams	Loamy clays, clays
Adequate B content of the soil (ppm B)	0.2 – 0.5	0.3 – 1.0	0.5 - 1.5
Fertilizer recommendation, kg/ha B	1.0 soil application 0.25 foliar application		

The recommended amount of boron to be applied depends on the clay and B contents of the soil (Table 28). If the B status is adequate, about 1-2 kg B/ha is advised as a soil application to avoid problems of B deficiency. Soil applications are most effective incorporated into the surface 15 cm of the soil (Nuttal *et al*., 1987). Recommended B rates in the form of foliar application are mostly lower (0.3-0.4 kg/ha). Similar values have also been reported in other regions of the world (Rashid *et al*., 1994; Kansar *et al*., 1990).

6.4.1.3. Foliar fertilization

Plant availability of boron is reduced by liming, by high soil pH and by drought periods during the main growth stages (Schröder, 1992). B deficiency symptoms appear often after hot, dry weather because less boron can be absorbed by plants as the top soil dries out. The decrease in availability probably results from boron becoming less mobile in the massflow to the roots (Kluge, 1971) and by polymerisation of boric acid (Marschner, 1995). After the soils are remoistened, uptake conditions for boron are improved so that more B becomes available and deficiency symptoms disappear (Shorrocks, 1997). Rape plants are thus particularly at risk of receiving an inadequate supply of B when growing on soils low in B and of high pH as well as in dry years.

Foliar applications of boron under such conditions of restricted availability especially may be more effective than soil application because the applied B can be directly taken up via leaves and is not fixed in the soil. From trials with *Brassica oleracera* it has been concluded that B deficient plants receiving foliar B fertilization give a higher yield than plants supplied with B only via the soil (Shelp *et al*., 1996).

The authors suppose foliar applied boron allows B a greater mobility, possibly combined with an access to a transport route inaccessible within the plant under unfertilized conditions.

In Polish field experiments (Krauze *et al*., 1991) on sandy loams and loam soils with a B content in the soil of 0.12-0.25 ppm and pH-values of 6.2-6.5, seed yield responses of 0.5-0.6 t/ha were found due to foliar spraying with boric acid (Fig. 56). In these investigations, seed quality was also improved. Fat content was increased significantly by 0.9%. The very low B content of plants at budding of 12-18 ppm B indicated a rather low B nutrition status of the rape crop. These results have been confirmed by three year field experiments in Germany in which 250 g/ha B boron were applied twice annually in a foliar form on each occasion together with Epsom salt which gave yield responses of 3-7% (Orlovius, 2001).

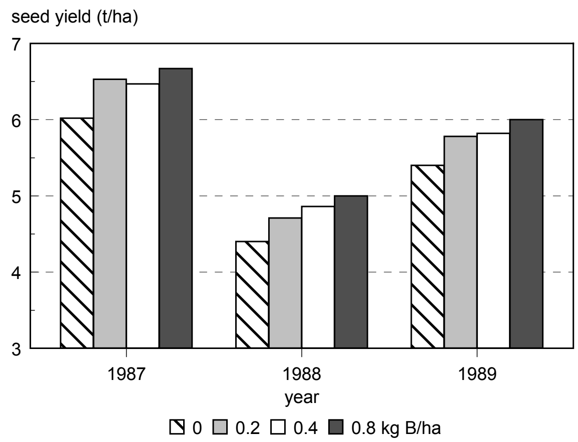

Fig. 56. Seed yield of winter oilseed rape grown under different levels of foliar applied boron (Krauze *et al*., 1991).

The major advantage of foliar application lies in the possibility of reacting very quickly following diagnosis of a deficiency and applying boron at particular stages of development. Restricted phloem mobility of boron is the reason for recommending spraying B not only as a single treatment but as repeated foliar treatments before and after the time of peak demand at flowering.

6.4.1.4. Boron fertilizers

Various borates can be used in applying boron either in solid form to the soil or as foliar fertilizer (Table 29). Differences in solubility of the borates including boric acid are of no great agronomic importance. All borates are easily dissolved in soils and quickly available if the surrounding conditions permit B uptake. Some crushed ores like Colemanite or Ulexite are used only for soil application, usually in a mixture with other fertilizers.

The narrow concentration range between deficiency and toxicity means that specialized knowledge required in the use of B fertilizers. Fertilizing for several years in advance, or application of B to seeds, or placement near the seeds or banded application implies a danger of toxic effects and for this reason these treatments are not recommended (Follett *et al*., 1981; Shorrocks, 1997). Boron toxicity may occur after applying large amounts of municipal compost (Purves and Mackenzie, 1974). In semiarid and arid areas the high B content of irrigation water can lead to B toxicity and should not exceed 10 mg B/l (Marschner, 1986). However, this value must be seen in context with the irrigated quantities of water and the B content in the soil. Because oilseed rape is relatively tolerant to B toxicity, other crops of the rotation show damage due to toxicity before oilseed rape. Symptoms of toxicity are chlorosis at leaf tips and margins followed by the progressive development of necrotic patches on the leaves.

Table 29. Commonly used agricultural borates (Shorrocks, 1997).

Refined products		B %
$Na_2B_4O_7{\cdot}5H_2O$	Sodium tetraborate pentahydrate	14.9
$Na_2B_8O_{13}{\cdot}4H_2O$	Solubor	20.8
$Na_2B_4O_7{\cdot}10H_2O$	Sodium tetraborate decahydrate (borax)	11.3
$Na_2B_4O_7$	Sodium tetraborate	21.4
$B(OH)_3$	Boric acid	17.5

6.4.2. Manganese

Most soils contain an adequate level of available manganese. However, some podzolic soils and highly leached tropical soils are low in Mn content and Mn deficiency may be observed. On such soils a Mn soil application of about 30 kg Mn/ha generally as $MnSO_4$ can correct deficiency (Mengel and Kirkby, 2001).

On other soils the most important reasons for manganese deficiency are reduced mobility and availability in the soil due to high soil pH, as may also be the case after liming, or with high organic matter content, and during periods of drought during vegetative growth. For this reason Mn fertilization via the soil is often not very effective because Mn is rather rapidly fixed in the soil to the non-plant available Mn oxide forms. Hence, most recommendations favor foliar applications under such conditions. Rates of 0.5-1.0 kg Mn/ha mostly as $MnSO_4$ are suitable to correct deficiency in the form of foliar fertilization. The main Mn requirement for rape begins with the onset of shooting, thus Mn foliar treatments should start at the latest at this stage. If Mn chelates are used the Mn rates should not exceed 0.1-0.2 kg Mn/ha. In cases of severe deficiency repeated applications from shooting until flowering are effective.

In German 3-year field experiments on sandy and loamy soils on different sites, a foliar application of 250 g/ha Mn in the of form of Mn sulphate together with Epsom salt and boron applied twice annually led to an increase in manganese content in the leaves by 10 ppm (Fig. 57).

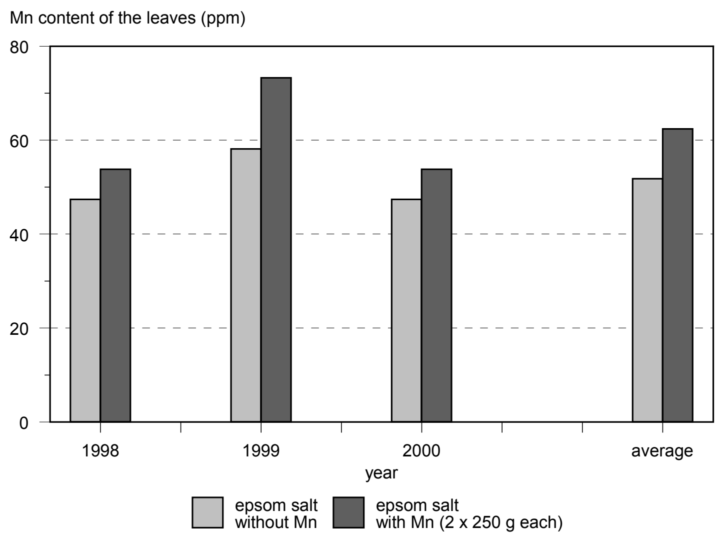

Fig. 57. Effect of a foliar fertilization with 2 x 250 g/ha Mn together with Epsom salt on the Mn content of oilseed rape leaves at different sites over three years.

On soils of high pH the use of soil acidifying fertilizers can improve the Mn supply to rape plants. Fertilizers like ammonium-sulphate, ammonium-sulphate-nitrate or elemental sulphur give rise to acidified zones in the areas surrounding the fertilizer particles and allow the plants to take up Mn more easily. For example on a carbonate free sandy loam with a pH of 6.0 the Mn content of rape leaves was increased by 63% through the use of ammonium-sulphate in comparison to calcium-ammonium-nitrate (Schnug and Fink, 1981). However, on carbonate containing soils even high doses of acidifying nitrogen cannot increase Mn supply.

6.4.3. Copper

Copper deficiency has rarely been observed in rape crops. Oilseed rape is more tolerant to low Cu supply than are cereals or flax (Mc Andrew *et al.*, 1984). Copper deficiency occurs mainly on diluvial sandy soils which are naturally poor in

Cu. With rising content of soil organic matter the risk of deficiency increases because the strong bond formed between Cu and N of humic and fulvic acids decreases Cu availability. Thus in naturally fertile soils like chernozems Cu deficiency has also been observed (Alloway and Tills, 1984).

High application rates of liming materials may induce a lack of copper, if such fertilization does not lead to a high mineralization of soil organic matter liberating copper ions for plant uptake. Soils developing from chalk or limestone materials are often poor in Cu and the likelihood of Cu deficiency has to be taken into consideration, although oilseed rape is not regarded as a crop which is highly sensitive to Cu shortage. On such soils foliar applications in the form of inorganic salts (mainly Cu sulphate), oxides or chelates are used to correct Cu deficiency. Cu rates of 0.5-1.0 kg/ha are recommended. However, the sulphate form may be less suitable because of the risk of foliar damage (Mengel and Kirkby, 2001).

Soil applications of inorganic salts, oxides or metal compounds are often advised and have a long-term effect. The amount of Cu fertilizers applied to the soil must exceed crop uptake considerably, rates of about 5 kg/ha Cu are usually adequate on Cu deficient mineral soils. The relatively high Cu content of pig slurry (about 25-35 g/m^3) should be considered if planning fertilizer treatments.

6.4.4. Zinc

Rape crops do not appear to be very sensitive to low zinc supply. However, with intensification of agricultural production the micronutrient zinc has attracted an increasing research interest particularly in tropical and subtropical regions. For example results from soil analyses in a micronutrient project in India indicate a high proportion of Zn deficient soils which can attain 60-80% of the total soils of some states (Tandon, 1989). Zn shortage is observed either on highly weathered acid soils that are often very poor in zinc or on calcareous soils. On naturally high pH soils or on highly limed soils, zinc mobility and availability is reduced mainly because of the adsorption of zinc to $CaCO_3$ or clay. Thus, the zinc concentration in soil solution falls with increasing pH. Moreover, Zn uptake is reduced by high concentrations of bicarbonates.

Zinc is mainly moved by diffusion. Hence, all factors which reduce the diffusion of Zn to the plant roots or the development of the root system also restrict zinc supply. For this reason, the risk of plant roots encountering a lack of zinc increases on compacted soils and under cold conditions. However, only few results of experiments with rape crops have been published. In pot experiments zinc application increased the pod number per plant (+24%) to a greater extent than the seed number per pod (+5%) or the 1000-seed weight (+11%) (Changzki *et al*., 1991). The Zn concentration of the seeds increased only slightly from 58 to 67 ppm Zn when Zn fertilization was raised from 1 to 150 ppm whereas analysis of the roots and stems revealed increases from 38 to 82 ppm and 27 to 134 ppm Zn respectively.

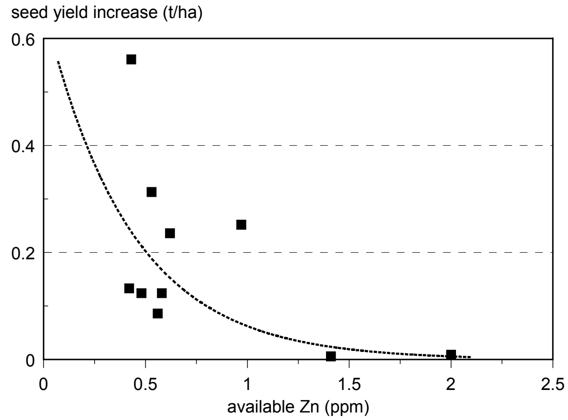

Fig. 58. Relationship between soil Zn status and crop response to Zn application of 15 kg/ha $ZnSO_4$ (after Changzki *et al*., 1991).

In field experiments on 16 locations with different soils in which available Zn in the soil ranged from 0.4-2.0 ppm in the main rape producing areas in the Hubei province of China, application of 15 kg/ha $ZnSO_4$ increased the averaged seed yields by 13% (8-19%) (Changzki *et al*., 1991). Yield responses depended on the content of available Zn in the soil. However, this relationship was not very close (Fig. 58). Oil content was enhanced by 0.9% whereas glucosinolate content decreased from 6.4 to 5.7‰ when zinc fertilizer was applied. Grewall *et al*. (1997) ascertained considerable differences in zinc efficiency between varieties of rape as well as of mustard genotypes.

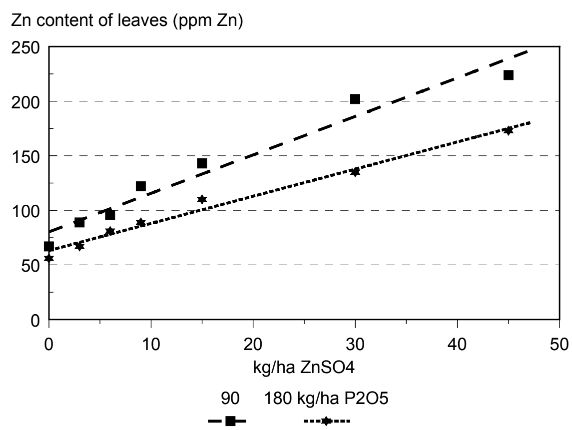

Fig. 59. Effect of increasing Zn fertilization on Zn content of youngest mature leaves of oilseed rape at two levels of P fertilization (Hu *et al*., 1996).

6.4.4.1. Interactions

On soils with a high phosphorus content or after high phosphorus applications an increasing risk of zinc shortage should be considered due to a Zn/P-interaction (Marschner, 1995). Thus, on soils low in available zinc, high rates of P fertilizer may increase the zinc requirements of plants. Besides additional phosphorus-zinc interactions within the plant the following main factors may be responsible for inducing a Zn deficiency: 1) a dilution of zinc in the plant by enhanced growth due to improved P nutrition and 2) an inhibition of Zn uptake by the cations added with phosphorus fertilizers (Ca^{2+} in particular with SSP).

In a field experiment in China on a silty clay with 0.56 ppm Zn in the topsoil and 0.25 ppm Zn in the subsoil (DTPA extractable) the increase of the phosphorus fertilization from 90 to 180 kg/ha P_2O_5 led to a decreased zinc content in youngest mature leaves of oilseed rape at the green bud stage (Fig. 59). Additionally, the Zn content in the plant increased to a larger extent by increasing the Zn supply at the lower rate of P fertilization in comparison with the higher P rate (Hu *et al*., 1996).

6.4.4.2. Zn fertilizer recommendations

Zn fertilizer recommendations are generally given for Zn deficient soils. On light soils with low Zn content rates of about 3-6 kg/ha Zn in the form of soil application are advised every three years. For medium and heavy soils the recommended rates increase up to 15 kg/ha Zn (for three years). Zn sulphate is the most commonly used Zn fertilizer because of its high solubility and favorable price. On soils in which plant available Zn is low, foliar spraying with Zn sulphate (0.2-0.4 kg/ha Zn) or Zn chelates (0.05-0.1 kg/ha Zn) are also often used.

6.4.5. Molybdenum

The total molybdenum content of the soil is relatively low compared to other micronutrients with values between 0.3 and 5 ppm. Low Mo contents are found on acid sandy soils and in areas of high rainfall (Bergmann, 1992). Although oilseed rape is of medium sensitivity to Mo deficiency, the deficiency is rarely observed in rape crops. However, soil pH has a considerable influence on the availability of molybdenum to plants (Falke *et al*., 1988). In contrast to most other micronutrients, Mo availability increases with rising pH of the soil.

High fertilizer rates of sulphur may induce Mo deficiency by direct uptake competition of molybdate and sulphate ions. This may be of importance on sulphur deficient soils. Under unfavorable conditions for molybdenum uptake, high sulphur application rates may lead to Mo deficiency and yield responses to Mo fertilization can be expected (Schnug and Haneklaus, 1990).

6.4.5.1. Mo fertilizer recommendations

The relationship between plant Mo content and soil pH is closer than between plant Mo content and soil Mo content (Massumi, 1967). For this reason, a so called "molybdenum soil index" was introduced in Germany to characterize soil Mo status (Müller *et al*., 1964). This index is calculated as pH-value +10-times the extractable molybdenum content of the soil (after Grigg, 1953). For an adequate Mo status the Mo soil index should be higher than 7.0 on light soils, 7.8 on moderately light and 8.2 on medium and heavy soils (Table 30; Kerschberger and Franke, 2001).

Table 30. Molybdenum soil index as base for Mo fertilizer recommendation (Kerschberger and Franke, 2001).

Sandy and light loamy sand soils	Loamy sands	Sandy loams, loams and clay	Mo availability, Mo recommendation
< 6.4	< 6.8	< 7.2	low, considerable yield response after Mo fertilization
6.4 – 7.0	6.8 – 7.8	7.2 – 8.2	medium, Mo fertilization recommended if soils are not limed
> 7.0	> 7.8	> 8.2	high, Mo fertilization not requisite

Mo soil index = pH + 10 x mg Mo/kg soil (extract. Mo content of the soil).

Plant availability of Mo may be low particularly on acid soils in which iron oxides accumulate because molybdenum binds to these compounds and availability is depressed despite the high amounts of Mo which can be released by soil extractants. Tissue analysis is probably a more reliable method of evaluating the Mo status of rape although it gives only a short-term evaluation. As observed by several authors a concentration of 0.3-0.6 ppm Mo in young fully developed leaves is necessary to achieve optimum yields (s. Table 16).

A good means of improving the Mo supply of the plants is to adjust of the optimal pH of the soil. Several examples show that liming treatments are similarly as effective in correcting Mo supply as fertilization with molybdenum (Kline, 1955; Kamperath and Foy, 1971). It should also be remembered that the use of physiological acid fertilizers like ammonium-sulphate or urea may impair the Mo status of plants (Schnug and Finck, 1981).

On Mo deficient soils and where the pH is already in the optimal range Mo treatment of the seeds is an effective means of ensuring molybdenum supply. 15 g/ha Mo with the seeds increased the Mo content of the leaves from 1 ppm to over 4 ppm (Podlesak and Krähmer, 1988).

Soil fertilization with molybdenum should only be made where liming treatments are not necessary or possible. Only small Mo rates are needed in the range between 400 to 800 g/ha Mo (Bergmann, 1992). When the Mo status is found to be inadequate during the growth period as measured by tissue analysis, foliar fertilization should be made as a fast effective treatment between shooting and the onset of flowering. Application rates of 30-300 g/ha Mo are recommended (Bergmann, 1992; Schnug and Haneklaus, 1990). In field experiments carried out over two years on nine Mo deficient locations in Germany, average yield responses of 0.11 t/ha (ranging from -0.05 and 0.27 t/ha) and 0.06 t/ha (ranging from -0.09 and 0.35 t/ha) were found after Mo foliar fertilization (Finck and Sauermann, 1998).

6.4.5.2. Molybdenum fertilizers

As fertilizer sources the water-soluble sodium- and ammonium-molybdates are widely used. They are suitable for soils as well as for foliar application. Water insoluble Mo fertilizers like molybdenum trioxide must be converted in the soil to molybdates to become plant available and are less used. For soil applications molybdenum is mostly mixed with other fertilizers, for example with superphosphate, to achieve a better surface distribution of the very low rates of Mo applied.

7. Oilseed rape in the crop rotation in relation to plant nutrition and plant protection

Alterations in crop rotation influence yield formation, yield components and yield level of all cultivated crops of the crop rotation. One particular crop may exert considerable favorable or unfavorable influences which can act as quickly as to affect the succeeding crop in the following year whereas the consequences of other pre-preceding crops may often not be observed until after a period of some years. The effects can differ between individual years depending on weather conditions and cultivation techniques.

7.1. Effect of preceding crops on oilseed rape

7.1.1. Yields

Oilseed rape is not self-compatible within the crop rotation (Sieling *et al.*, 1997). From a long-term crop rotation trial in northern Germany, it can be clearly concluded that rapeseed yields fall as the crop increases in its share of the crop rotation (Fig. 60). Oilseed rape as a monoculture (100% share) led to the lowest seed yield of 3.13 t/ha whereas for oilseed rape cultivated only every 5 years (20% share) a higher yield level of 0.44 t/ha was obtained. Pod number per plant and seeds per pod reacted very sensitively and gave the lowest values in the rape after rape rotation, whereas seed weight differed only slightly.

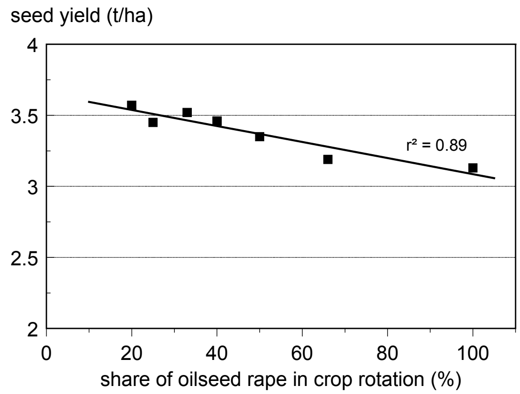

Fig. 60. Impact of the share of oilseed rape in the crop rotation on seed yield of oilseed rape (Sieling *et al*., 1997).

The influence of the directly preceding crop may modify the effect of the rape share within the crop rotation (Christen and Sieling, 1994). The highest yields of oilseed rape were always achieved after peas as preceding crop followed by barley and wheat (Fig. 61). However, the beneficial effect of peas did not occur when the rape share in the rotation exceeded 50%.
Besides the reduction of pods and seeds, increasing incidence of diseases also determines the lower yield. The incidence of stem canker (*Leptshaeria maculaus*) and verticillium wilt (*Verticillium dahliae*) were significantly higher when rape followed rape compared with all other preceding crops (Sieling *et al*., 1997). The highest seed yield losses of rape arose after rape as preceding crop when no fungicide treatments were given.

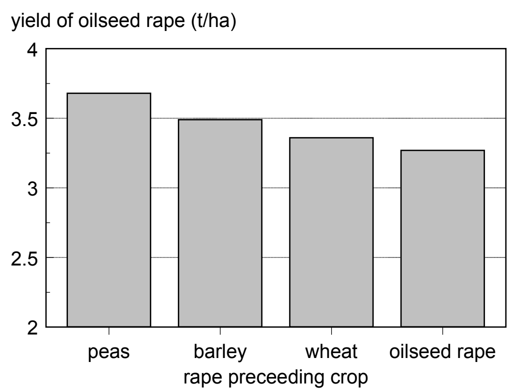

Fig. 61. Influence of different rape preceding crops on seed yields of oilseed rape (Christen and Sieling, 1994).

7.1.2. Diseases

The occurrence of disease was found to increase as the contribution of rape to a crop rotation became more dominant (Makowski, 1998). In a 13 years long-term rotation trial, the incidence of all important rape diseases rose if the rape share of the rotation was extended from 17% to 33%. Particularly *Phoma lingam, Sclerotinia sclerotiorum, Verticillium dahliae, Plasmodiophora brassicae, Cylindosporium cincentricum, and Pseudocercosporella capsellae* were favored in rape intensive crop rotations (Fig. 62). This finding shows the necessity of taking particular care in rape intensive crop rotations in matters concerning plant protection. Stress occurring around flowering especially severely affects seed yield of oilseed rape because of restricted ability in being able to compensate at a later stage (Tayo and Morgan, 1979).

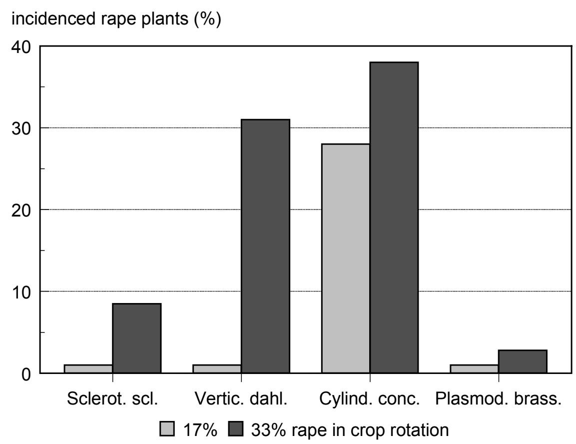

Fig. 62. Influence of different share of oilseed rape in the crop rotation on the incidence of rape diseases (Makowski, 1998).

7.1.3. Fertilization

The crop rotation influences the optimum nitrogen fertilizer rate to achieve optimum yield. Interactions between the preceding crop and N fertilization have been observed. In Swedish field trials in which the optimum N fertilizer rate could be reduced from 90-120 kg/ha N to 60 kg/ha N if peas or fallow rather than winter wheat preceded the rape crop (Andersson, 1990). Similar interactions were found in northern Germany in long-term crop rotation trials (Sieling and Christen, 1997). The disadvantages of rape as a preceding crop for rape were particularly high when N fertilizer rates were low, from 80-120 kg/ha N, whereas the differences became smaller with increasing amounts of applied nitrogen (Fig. 63). In the crop rotation rape-wheat-wheat, the optimum seed yield of rape was achieved already with N rates of 120-160 kg/ha N whereas 200 kg/ha N was necessary in a crop rotation of rape-rape-cereals.

Fig. 63. Effect of different crop rotations on the seed yield of oilseed rape at different N fertilizer levels (Sieling and Christen, 1997).

7.2. Effect of oilseed rape as preceding crop

7.2.1. Yields

Several investigations have reported a special value of oilseed rape as a preceding crop for following wheat, comparable with other leafy root-crops. The value of rape as a preceding crop relates mainly to improvement of soil structure through intensive soil shading and the dense rooting system in the top- and subsoil. Additionally the relatively large mass of easily mineralizable crop residues of rape constitutes a good basis for the nutrition of microorganisms of the soil and improves soil microbial activity for the following crop.

Results from a long-term crop rotation trial on a high fertile marsh soil documents a yield advantage of 1.0 to 1.3 t/ha for wheat after rape compared with a pure cereal rotation of wheat monoculture (Fig. 64; Teuteberg, 1980). Such results are confirmed by another long-term crop rotation trial on a sandy loam where wheat yields were higher on average by 1.1 t/ha with rape as preceding crop in comparison to wheat (Christen and Sieling, 1998). This mean value differs significantly from year to year.

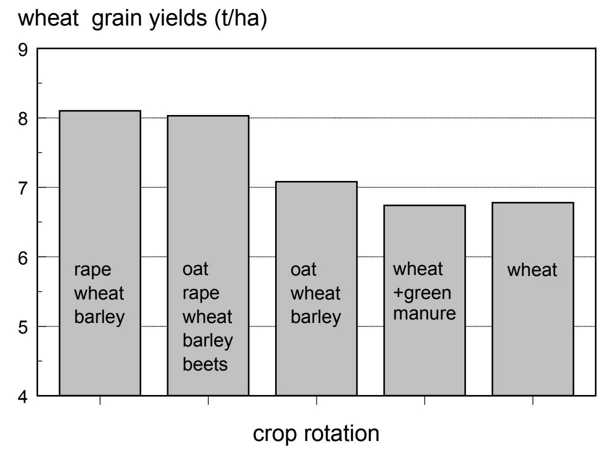

Fig. 64. Effect of including oilseed rape in the crop rotation on the grain yields of wheat (Teuteberg, 1980).

Especially in years with an above average yield (1991 or 1995) the advantage of oilseed rape as a preceding crop for wheat becomes particularly apparent with grain yield differences up to 2.5 t/ha (Fig. 65). This fact underlines the importance of oilseed rape in crop rotations with wheat.

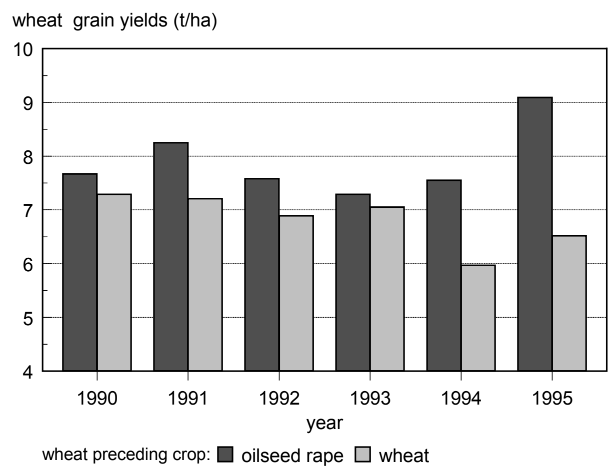

Fig. 65. Grain yields of wheat grown after oilseed rape or after wheat (Christen and Sieling, 1998b).

7.2.2. Fertilization

Rape as a preceding crop has a considerable effect on the N efficiency and the optimum N fertilizer rate. For example wheat after oilseed rape produced higher grain yields at all N fertilizer rates compared with wheat after wheat (Fig. 66). Additionally the optimum N rates for maximum wheat yield lay 60-80 kg/ha N lower than for wheat after wheat. Hence, nitrogen supplied as fertilizer to wheat following oilseed rape is better converted into wheat grain yield. N fertilizer efficiency for wheat is therefore improved by oilseed rape as a previous crop (Christen, 1998).

With regard to the profitability of a whole crop rotation it has to be considered that the detrimental effect of wheat as a preceding crop for wheat in terms of yield could not be fully compensated for by increasing rates of N fertilizer. The cultivation of oilseed rape additionally increases the yields of wheat besides providing other advantages in husbandry and organization of work. This may be dependent on a lower level of disease especially with take all (*Gaeumannomyces graminis*) if oilseed rape is included in the crop rotation (Christen *et al.*, 1992; Christen and Sieling, 1993).

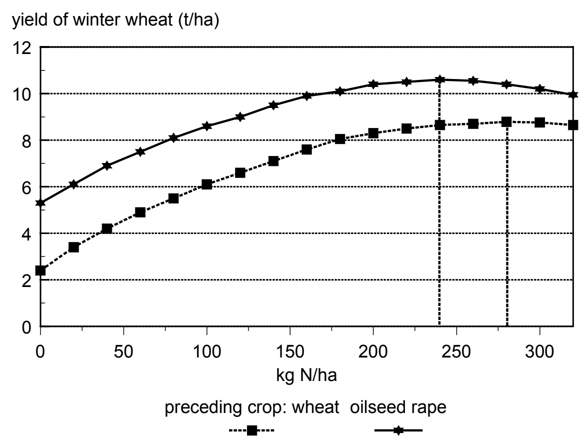

Fig. 66. Effect of the preceding crops wheat or oilseed rape on the yield of wheat at different N fertilizer rates and on the N fertilizer optimum (Christen, 1998).

7.3. Stress and disease resistance and nutrient supply

The nutrition of a crop obviously affects its tolerance to abiotic stress and its resistance to biotic stress. It is well known that infestation of plants by pathogens may depend on the nutritional status of the plant. Fertilizer application may influence the response of plants to pathogens directly or indirectly. For example by improving growth and closing the canopy, fungal infection is affected by changed microclimate. This non-specific effect is often caused by the generous use of nitrogen (Budzýnski and Jankowski, 2000). Nutritional status affects plant ability to prevent disease. Stomatal movement is important when pathogens like bacteria and some fungi enter a plant through the stomata. In K-deficient plants, stomata remains open longer, favoring infection (Trolldenier, 1971).

The plant's ability to regenerate diseased organs may also be influenced by the nutrient supply. High nitrogen supply generally increases susceptibility to disease but on the other hand enhances regeneration, compensating the damage caused by disease (Garett, 1970).

An extensive compilation of literature was published concerning the effect of potassium on plant health (Perrenoud, 1990). From these data it seems that potassium generally improves plant health and is most effective against fungal and bacterial diseases and is without clear effect on nematodes and viruses (Table 31).

Table 31. Effect of potassium on the incidence of diseases and pests (Perrenoud, 1990).

Parasite group	Total number	% of indications		
		incidence decreased	incidence unchanged	incidence increased
Fungal diseases	1549	70	7	23
Insects + mites	459	63	9	28
Nematodes	111	33	4	63
Viruses	186	41	7	52
Bacteria	144	69	10	21

Furthermore the balance between nitrogen and potassium is of particular importance. Whereas a high nitrogen supply tends to decrease resistance, potassium has the opposite effect. Thus, the ability to resist fungal and bacterial diseases depends on the N:K ratio (Fuchs and Grossmann, 1972). In many cases potassium reduces the detrimental effects of nitrogen on plant health. However, only very few data are available about such nutritional effects on the oilseed rape crop.

For the nutrient sulphur, evidence is increasing that S is involved in several response and tolerance mechanisms to biotic and abiotic stress (Schnug *et al.*, 1995; Harms, 1998). Oilseed rape has a high S demand so that this characteristic is of particular importance for this crop. During sulphate reduction the very small gaseous losses (mainly as H_2S) play an important role in plant resistance to diseases, because H_2S is a very effective fungicide (Schnug and Haneklaus, 1994b). Sulphur deficiency thus increases susceptibility to fungal attack.

Furthermore, several other S containing secondary plant products are linked to the resistance of oilseed rape to fungal diseases. The glucosinolates which are affected by sulphur supply particularly influence the plant's defense system against diseases (Schnug and Ceynowa, 1990). Growing a highly susceptible variety with a high and a low sulphur supply, both sets of plants inoculated with *Alternaria brassiciola* (Walker and Booth, 1994) resulted in different glucosinolate contents in the plants. These contents related to S supply and 10 days after inoculation the plants fertilized at the higher rate of sulphur showed less than half the disease level of the plants at the lower S level (Fig. 67).

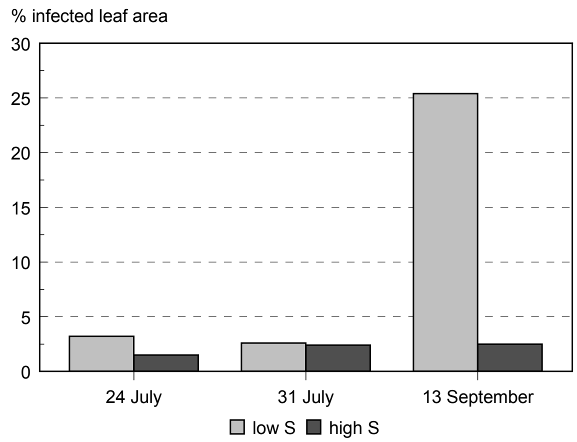

Fig. 67. Effect of sulphur on *Alternaria brassiciola* (24, 31 July) and *Erysiphe cruciferarum* (13 September) infection expressed as a percentage of leaf area infected (Walker and Booth, 1994).

Moreover, for the plants supplied at the higher level of S nutrition there was a beneficial effect six weeks later in a comparative reduction in the incidence of a natural infection with *Erysiphe cruciferarum*. The infected leaf area decreased from 25% to 2.5% with improved sulphur status of the plant. In other investigations the infection with *Phoma* decreased considerably with increasing glucosinolates content (Koch, 1989). These results indicate that stress resistance of oilseed rape may be reduced by an insufficient S supply and consequently, increasing sulphur fertilization can help to reduce and delay disease infection and possibly reduce chemical inputs.

In experiments with *Brassica oleracea* the correlation between pH soil and the finger-and-toe disease (*Plasmodiophora brassicae*) has been demonstrated (Lattauschke, 2001). This fungal disease appears mainly from too frequent use of cruciferae species in the crop rotation. For this reason, the first possibility to control this disease lies in changing the crop rotation widening the periods between cultivation of Brassica species and particularly oilseed rape. If the infection potential in the soil is not too high liming the soil can also control this disease. A high soil pH reduces germination of the spores and thus restricts infestation of the roots. With increasing rates of applied burnt lime the proportion of plants attacked by the disease decreased significantly as a consequence of increasing soil pH (Fig. 68).

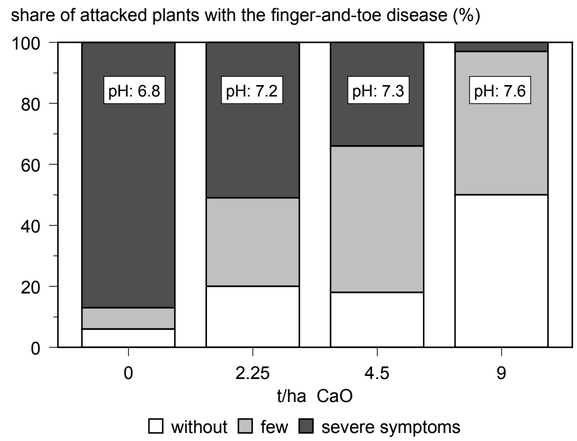

Fig. 68. Effect of different treatments with burnt lime on the infestation with the finger-and-toe disease (*Plasmodiophora brassicae*) of *Brassica oleracea* (Lattauschke, 2001).

7.4. Environmental effects of oilseed rape

High yielding oilseed rape seems to be a N inefficient crop. Fismes *et al*. (2000) found values for the apparent N use efficiency of only 40-50% which is considerably lower compared with cereal crops in which 75-90% is reached (Delogu *et al*., 1998). In oilseed rape considerable amounts of nitrogen are found in the straw at harvest because the crop is obviously unable to transfer all the nitrogen from leaves and stems into the seeds (Schjoerring *et al*., 1995). The N balance of high yielding oilseed rape is therefore nearly always positive with a surplus not usually less than 80 kg/ha N and sometimes more (Gäth, 1997; Wiesler, 1999).

Apart from its positive value as preceding crop for a following cereal crop (s. chapter 7.2) the cultivation of oilseed rape from an ecological viewpoint must be considered in terms of the possibility of increased nitrate losses during autumn and winter. These may be translocated into the deeper soil layers and inaccessible to the roots of the following cereal crop. This has to be taken into acccount particularly on sites with a low water storage potential and the problem approached through special husbandry techniques. By cultivating a successful intercrop for example of *Phacelia* about 30-40 kg/ha N can be conserved biologically (Lickfett, 1997).

On the other hand, a well-established winter oilseed rape crop is able to take up about 70 kg/ha N in autumn before winter. In the case of an early sown crop with a luxuriant canopy this amount may increase up to 180 kg/ha N (Schulz and Schumann, 2000). Cultivation of oilseed rape therefore reduces the leachable N pool in the soil from the preceding crop due to its large N uptake. Additionally, the drainage volume decreases due to water use in autumn with the consequence of a later return to field capacity (Barraclough, 1989; Aufhammer *et al*., 1994). Thus, the potential of N leaching is reduced and winter oilseed rape can be a suitable crop for conserving nitrogen throughout the winter.

8. Concluding remarks

Oilseed rape is being grown throughout the world in increasing amounts. The uses of oilseed rape are very varied in human and animal nutrition as well as for technical purposes and in the chemical industry. Of the means available to increase economic yield, adequate nutrient supply and optimized fertilizer use play an important role. To safeguard high yields and to utilize the yield potential of new varieties to their full extent, nutrient availability has to be optimized. The farmer needs to make best use of efficient and balanced fertilizer application. This includes not only the traditional macronutrients nitrogen, phosphorus and potassium, but also magnesium, sulphur and lime as well as the micronutrients.

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