quality of compost for soil remediation is completely different from the quality needed in horticultural substrates.
The methods for chemical characterization of composts are well established. Both nutrients and heavy metals are routinely analyzed. The physical and biological aspects of compost quality, which have an important influence on the positive effect of composts on plants or soils are, however, not consistently determined. In order to estimate the potential of Swiss composts to positively influence soil fertility and plant health, we analyzed one hundred composts and digestates representative of the different composting and methanization systems and also representative of the qualities available on the market.

2 Material an Methods

Samples from one hundred and one composts and digestates were collected from different composting and methanization plants according to the guidelines and recommendations with respect to waste fertilizers (FAC 1995). All plants process only source-separated organic material. The samples were chosen in such a way that they are representative of the composts produced in Switzerland (tab. 1). The samples were either tested immediately after collection, or stored at 3°C until testing.

2.1 Chemical and biological characteristics of the composts

Nutrients and heavy metals were analyzed with ICP-AAS according to the official Swiss methods (Schweizerische Referenzmethoden, 2005). The stability of the organic matter in composts was characterized by spectrophotometric measurement at 550 nm. Measurements were made both with aqueous extracts (1:2 water extract (v:v) according to Schweizerische Referenzmethoden, 2005 (2005), and a pyrophosphate extract according to Kaila (1956).
The influence of compost on nitrogen mineralization in soil was determined with the incubation experiment according to the official Swiss methods (Schweizerische Referenzmethoden, 2005). Five to 10 percent of compost was added to a reference soil, placed in PVC boxes (12 x 10 x 5 cm, with aeration holes), wetted and incubated at 25°C. The mineralized nitrogen (NH_4 and NO_3) in the soil was determined after 0, 2, 4, 6 and 8 weeks.
The activity of four enzymes was determined: fluorescein diacetate according to Inbar et al. (1991), dehydrogenase, protease and cellulase according to Alef and Nannipieri (1995).
The respirometric activity was determined according to Bockreis et al. (2000).

2.2 Biotests

The phytotoxicity tests were performed according to Fuchs and Bieri (2000). In the open phytotoxicity tests, the growth of cress (*Lepidium sativum* L.), salad (*Lactuca sativa* L.) and bean (*Phaseolus vulgaris* L. var. *nanus* L) in pots (Ø 10 cm) filled with compost was compared with the growth in reference substrate BRS-200 (Biophyt Ltd, CH-Mellikon). In the closed phytotoxicity test, PVC boxes (1 liter) were half-filled with compost or reference substrate BRS-200, cress sown onto it, then the boxes were closed hermetically. The growth of the plants in the boxes was then observed.
Two disease suppressivity tests were performed: cucumber (Cucumis sativus)-*Pythium ultimum* and basil (Ocymum basilicum)-*Rhizoctonia solani*. Both tests were performed in 200-ml plastic pots. Compost (20 % v/v) was added to the soil. In the cucumber-*Pythium* test, the pathogen was grown for 7 days on autoclaved millet, then added to the soil. In the basil-*Rhizoctonia* test, the pathogen was also grown on millet which was placed on the bottom of the pots. Cucumber or basil was then sown. Damping-off of the cucumbers was evaluated 10 to 15 days after sowing. In the basil-*Rhizoctonia* test, the living plants were counted after one, two and three weeks.

Table 1 Repartition of the compost samples regarding their different characteristics

Characteristic	Classification	Number of samples
Origin of the material	urban	59
	rural	42
Composition	green waste only	52
	green waste with bio waste	49
System	thermophilic methanization	15
	mesophilic co-methanization	5
	triangular piles < 2m	16
	triangular piles > 2m	25
	table piles, open	7
	aerated boxes	5
	aerated canal or shed	4
	edges of fields	9
	combination of methanisation and composting	10
	combination of boxes and triangular piles	2
	vermicomposting	3
Product[1]	solid digestate	11
	liquid digestate	4
	compost for agriculture	34
	compost for horticultural use	36
	compost for covered cultures and private gardening	16
Turning technique	no turning	3
	trax	39
	turning machine	52
	combined trax and turning machine	2
Turning intensity	never turned	2
	<1x per week	45
	1x per week	20
	2-3x per week	29
	>3x per week	0
Hygienisation[2]	Criteria not fulfilled	14
	at least 3 weeks > 55°C	38
	at least 1 week > 65°C	47
Forced aeration	no forced aeration	64
	at the begining of the composting process	26
	during storage	3
	at the begining of the process and during storage	4
Humidity management	too dry	48
	optimal	40
	too wet	8

[1]: product description according to ASCP Guidelines 2001 (Fuchs et al., 2001)
[2]: according to the "Guidelines and Recommendations of the Research Centre for Agricultural Chemistry and Environmental Science with respect to waste fertilisers" (FAC 1995).

3 Results and discussion

3.1 Chemical characteristics of the Swiss composts

The chemical characteristics of the different composts are presented in tab. 2. The values for the different composts varied greatly. While the contents of salts, nitrogen, phosphorus, potassium, magnesium and calcium depends predominantly on the materials of origin, the organic matter and the density are more influenced by the maturity of the products. However, high variability was observed for all parameters within a product category. For example, the salt content, which should be low in the composts for covered cultures and private gardening, varied between 328 and 1539 [g KCL equivalent / 100 g fresh matter]. Through a more consistent choice of the materials of origin, the compost producers could obtain a more constant salt content in the final product.
The heavy metals contents in the Swiss composts are low and all the values are clearly under the Swiss limits. The only exception is copper, for which a few outliers exceeded the limit (100 mg|kg DM]. Copper and cadmium contents were constant for all product classes. By contrast, cobalt, nickel and zinc in the composts increased with the product classes (tab. 2). This can be explained on one hand by the concentration of heavy metals during mineralization of the organic matter, and on the other hand by the more fine sieving of these products, which removes mainly wooden particles.
The darkness of the water extract is an important characteristic of composts in view of their practical horticultural utilization. If compost with dark water extract is used for potted plants placed in front of houses, there is a risk of coloration of the house wall by run-off water. The material of origin had some influence on the darkness of the compost extract, but the major influence comes from the maturity of the compost (fig 1A). The humus forms of immature compost are water-soluble, and so their water extract is dark. During compost maturation, the small humus molecules are transformed to larger humus molecules which are not water-soluble, therefore the extract has a lighter colour. This evolution is evident in fig. 1A. The pyrophosphate extraction gives a better indication of stability than the water extract. Very young products such as digestates show a low pyrophosphate index (fig. 1B), because the lignified organic matter is not yet decomposed. The pyrophosphate index then increased significantly and the composts for agricultural use had the highest pyrophosphate index (fig. 1B). The stability of the humus forms, characterized by the decreasing of the index, has a slow evolution, and the variation within a product class is more important than between classes (fig. 1B). The influence of the composting materials seems to play a more important role that the maturation process, in view of the considered composting duration.

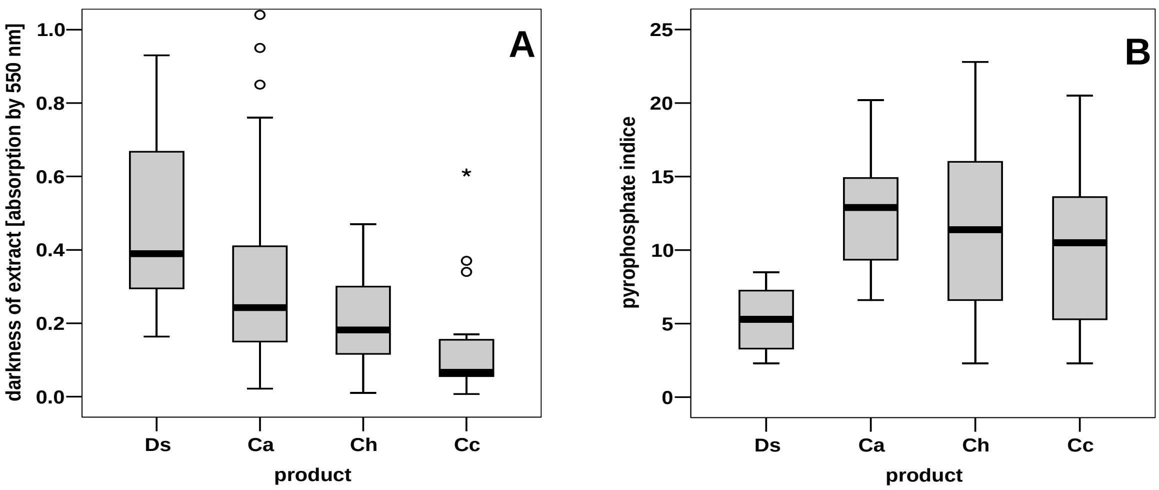

Figure 1 Stability of the organic matter of Swiss composts. A: darkness of the 1:2 water extracts (extraction according to ….). B: Pyrophosphate indice according to Kaila (1956). Composts were sampled according to ASCP Guidelines 2001 (Fuchs et al., 2001): Ds=digestate solid, Ca=compost for agriculture, Ch=compost for horticultural used, Cc=compost for covered cultures and private gardening.

Table 2 Chemical characteristics of Swiss composts[1]

	Digestate for agricultural use	Compost for agricultural use	Compost for horticultural use	Compost for covered cultures and private gardening
salt content[2] [mg KCl/100g FM] median (minimum; maximum)	970 (704; 1384)	862 (361; 1580)	787 (173; 2657)	660 (328; 1539)
pH[2] median (minimum; maximum)	8.5 (8.0; 8.8)	8.2 (7.5; 8.7)	8.1 (7.6; 8.7)	7.9 (7.2; 8.5)
density [g/l] median (minimum; maximum)	468 (321; 631)	556 (412; 851)	609 (434; 836)	715 (631; 904)
dry matter [% FM] median (minimum; maximum)	53.1 (45.4; 75.2)	50.8 (28.2; 73.4)	56.7 (40.8; 71.1)	56.3 (32.2; 64.5)
organic matter [% DM] median (minimum; maximum)	50.3 (28.9; 73.4)	47.7 (17.0; 80.1)	38.1 (23.9; 54.7)	30.6 (20.9; 52.8)
total N [g/kg DM] median (minimum; maximum)	15.3 (9.4; 20.3)	16.6 (8.7; 26.0)	14.6 (9.2; 27.6)	15.1 (8.6; 25.2)
total P [g/kg DM] median (minimum; maximum)	3. 6 (2.0; 8.0)	3.0 (1.7; 6.1)	3.0 (1.3; 12.7)	3.3 (2.1; 8.8)
total K [g/kg DM] median (minimum; maximum)	12.5 (6.4; 20.8)	12.0 (5.7; 25.2)	11.6 (2.2; 20.7)	10.7 (5.5; 27.8)
total Mg [g/kg DM] median (minimum; maximum)	6.8 (3.7; 9.7)	4.8 (3.6; 10.3)	6.5 (4.4; 10.7)	6.5 (4.4; 13.3)
total Ca [g/kg DM] median (minimum; maximum)	46.6 (23.0; 57.8)	53.1 (24.0; 83.7)	64.0 (35.0; 91.5)	44.5 (69.4; 29.5)
Fe [mg/kg DM] median (minimum; maximum)	8.9 (3.7; 12.3)	8.8 (2.9; 16.7)	10.1 (5.4; 14.7)	12.0 (6.1; 15.8)
Na [mg/kg DM] median (minimum; maximum)	1.3 (0.5; 2.0)	0.7 (0.3; 4.5)	0.6 (0.2; 1.9)	0.6 (0.3; 1.4)
Cd [mg/kg DM] median (minimum; maximum)	0.12 (0.01; 0.34)	0.12 (0.01; 0.53)	0.13 (0.01; 0.52)	0.13 (0.06; 0.45)
Co [mg/kg DM] median (minimum; maximum)	2.8 (1.4; 5.3)	3.5 (1.0; 6.4)	4.2 (2.7; 6.0)	4.8 (2.4; 6.3)
Cr [mg/kg DM] median (minimum; maximum)	21.0 (8.0; 31.1)	16.4 (2.3; 29.1)	19.9 (10.5; 35.1)	22.5 (10.3; 40.5)
Cu [mg/kg DM] median (minimum; maximum)	49.8 (21.3; 68.5)	48.4 (21.3; 295.8)	57.4 (33.9; 105.4)	52.5 (34.4; 334.8)
Ni [mg/kg DM] median (minimum; maximum)	13.7 (8.2; 17.0)	14.3 (2.9; 25.1)	15.9 (10.3; 25.1)	18.0 (8.8; 22.4)
Zn [mg/kg DM] median (minimum; maximum)	116.4 (6.6; 282.1)	140.5 (72.2; 260,0)	149.3 (108.7; 272.7)	161.4 (109.9; 252.2)

[1]: according to the "Guidelines and Recommendations of the Research Centre for Agricultural Chemistry and Environmental Science with respect to waste fertilisers" (FAC 1995).
[2]: value determined in 1:2 water extract

3.2 Characterisation of the biological activities of the Swiss composts

The evolution of the activity of four enzymes during composting differed greatly (fig. 2). The FDA (fluorescin diacetate activity) and the protease activity differed significantly between the different product classes (fig. 2). Their activities are decreasing with the advancement of product maturity. A similar evolution, but less evident, is observable in the cellulase activity. By contrast, the dehydrogenase activity was less influenced by the maturity of the products.

Respiration rate decreased with compost maturation (fig. 3), as already shown by different authors (Paletski and Young, 1995; Lasaridi and Stentiford, 1998; Popp et al., 1998).

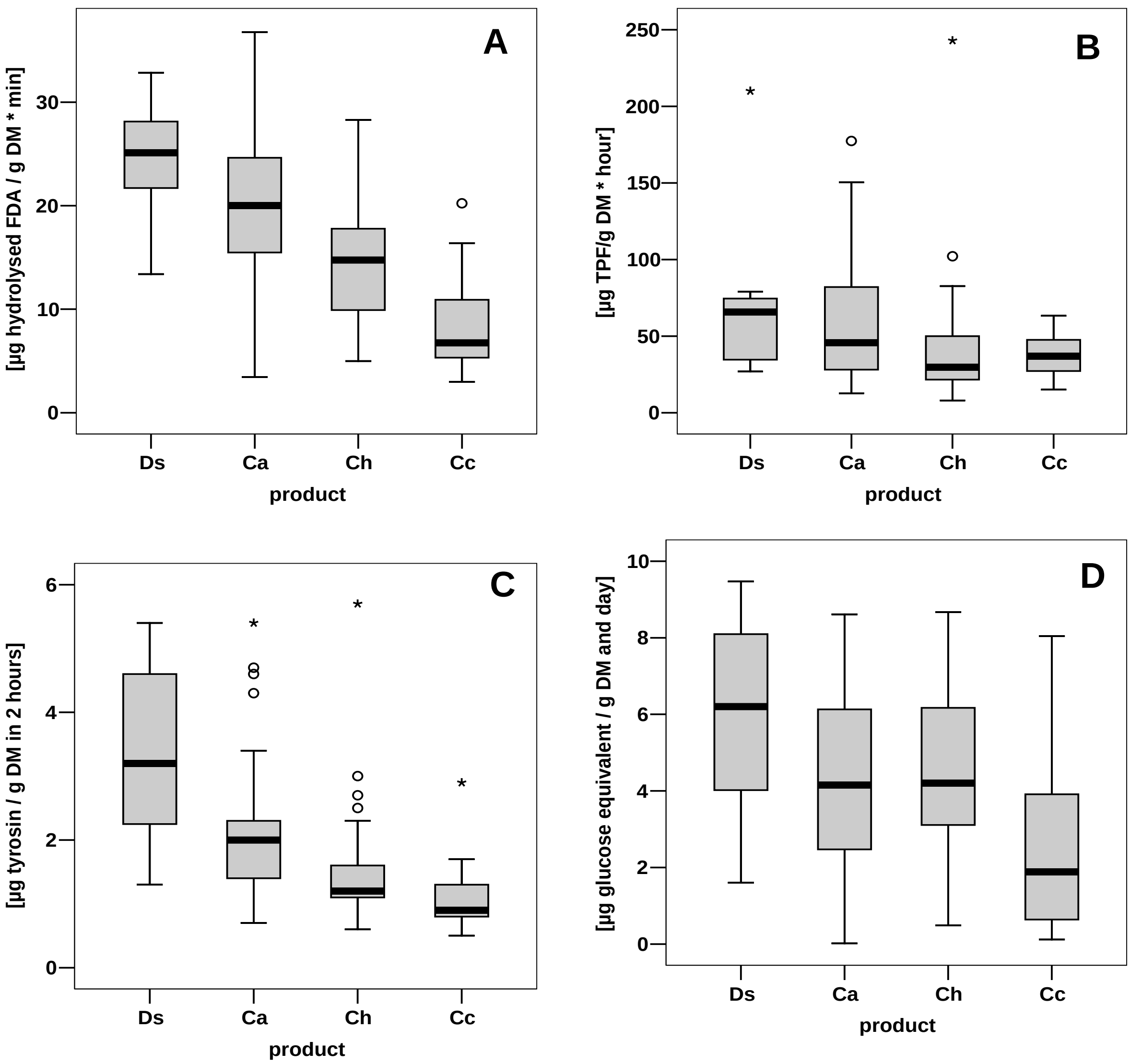

Figure 2 Enzymatic activities of Swiss composts. A: FDA activity; B: dehydrogenase activity; C: protease activity; D: cellulase activity. Products according to ASCP Guidelines 2001 (Fuchs et al., 2001): Ds=digestate solid, Ca=compost for agriculture, Ch=compost for horticultural used, Cc=compost for covered cultures and private gardening.

3.3 Influence of compost addition to soil on its mineralized nitrogen content

The influence of compost on the mineralized nitrogen content in soil depends, beyond the quantity of available nitrogen, also on the microbiological activity of the compost. Normally, digestates contain a high amount of mineralized nitrogen, mainly as ammonium, and they contain relatively low quantities in the form of lignin rich materials. Therefore, nitrogen immobilization is not expected after the utilization of such products. In practice, this is not always the case (fig. 4Ds). The reason for the immobilization of nitrogen in soil by some digestates is that these products are not used fresh, but after an inadequate subsequent treatment, during which the digestate is dry and all the ammonium is lost. In the other products, the evolution of the nitrogen immobilization risks can be clearly observed (Fig. 4). The composts for agricultural use are mainly young composts rich in undegraded lignin. The degradation of these woody substances in soil leads to a momentary immobilization of the available nitrogen (Fig 4Ca). When the composts are more mature, this risk decreased (fig. 4Ch and 4Cc).

3.4 Influence of compost on plant growth

Plants react on compost quality as a whole. Sometimes, all of the above-mentioned chemical parameters of a compost are good, but plants do not develop well in it for unknown reasons. To assess this risk, the phytotoxicity tests are used. The four phytotoxicity tests used react differently to compost quality. The cress test open is the least sensitive, and the plants showed growth depression only in the digestates (fig. 5Co). The salad test is more sensitive in the open system, and only the more mature products allowed a good growth of the plants. In the closed cress test, the plants are not only in contact with the compost, but are also strong influenced by the gases which evaporate from the compost. This test is therefore very sensitive, and only the compost with high plant compatibility allowed a good growth of the cress.

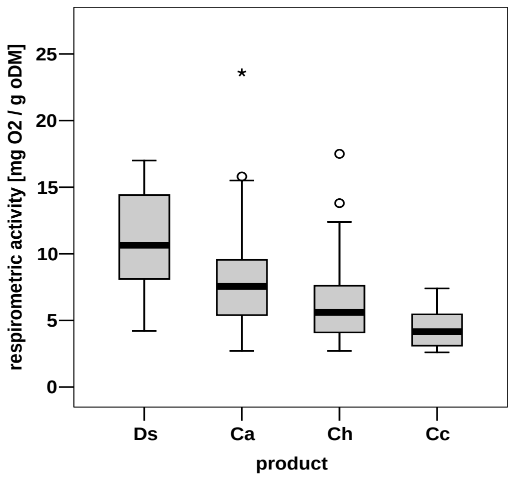

Figure 3 Respirometric activity of Swiss composts. Products according to ASCP Guidelines 2001 (Fuchs et al., 2001): Ds=digestate solid, Ca=compost for agriculture, Ch=compost for horticultural used, Cc=compost for covered cultures and private gardening.

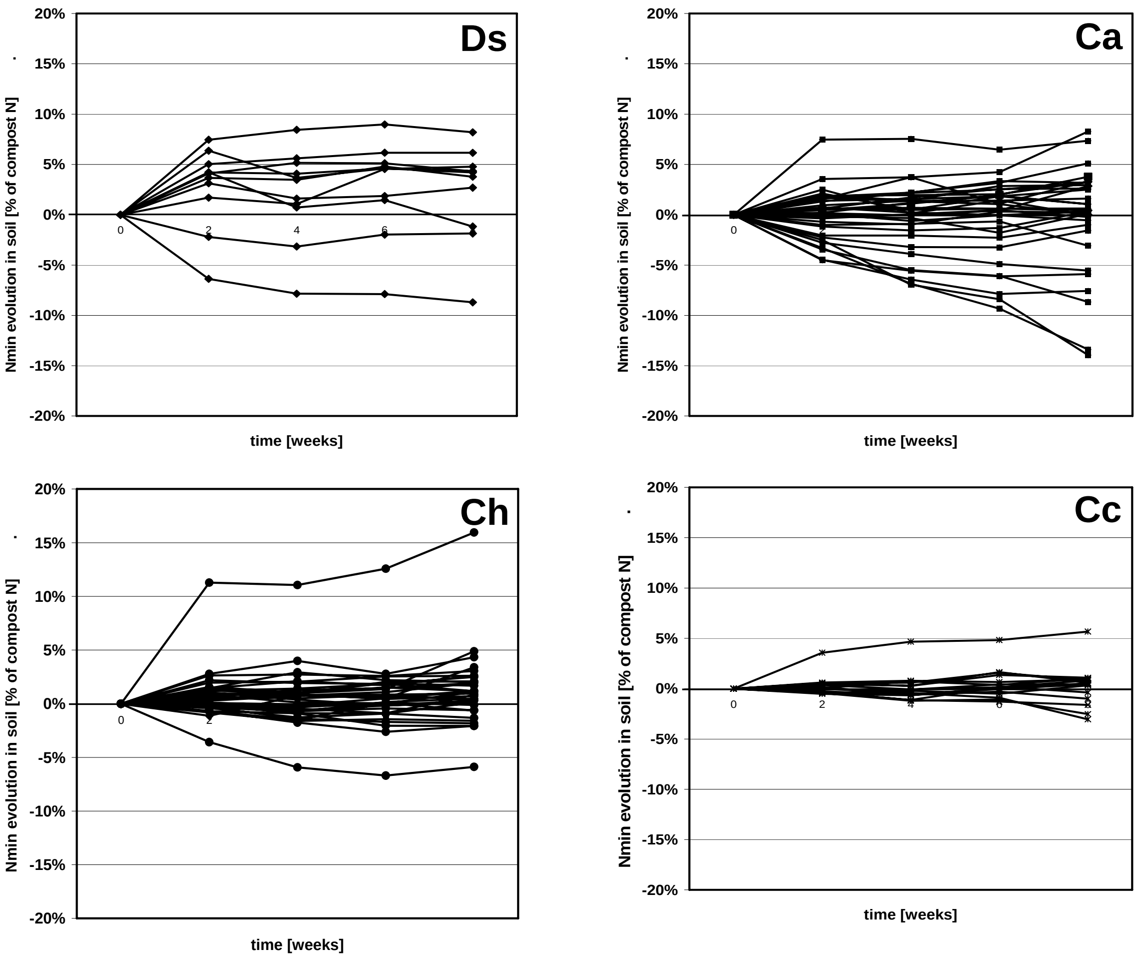

Figure 4 Influence of the addition of different composts to soil on the evolution of its mineralized nitrogen content. For each compost, the mineralized nitrogen after 2, 4, 6 and 8 weeks are compared to the mineralized nitrogen present in the soil immediately after compost addition. Products according to ASCP Guidelines 2001 (Fuchs et al., 2001): Ds=digestate solid, Ca=compost for agriculture, Ch=compost for horticultural used, Cc=compost for covered cultures and private gardening.

In all test systems, an evolution in the plant compatibility was obvious, with the plants growing better in more mature composts (fig. 5). Nevertheless, there was considerable variation within a product class. This fact shows that the management of the composting is at least as important for the biological quality as the maturation advancement.

3.5 Capacity of Swiss compost to protect plants against soil borne diseases

The suppressive potential of the composts against two pathogens was tested: *Pythium ultimum* and *Rhizoctonia solani*. *P. ultimum* is mainly causing damage during germination; once the plant is big enough, this fungus usually causes no more important damage. *R. solani* can attack the plant later and cause important damage also to larger plants.

No differences in the capacity of the composts of the different products classes to protect cucumber against *P. ultimum* were observed. The great majority of the composts significantly reduced the incidence of the disease caused by this pathogen (fig. 6P). The protection of basil against *R. solani* was clearly less efficient (fig. 6R). It seems that the capacity of the composts to protect basil against *R. solani* reached a maximum at the stage Ch (fig. 6R). In accord with other authors, we assume a general protection mechanism for *P. ultimum* and a specific mechanism in the case of *R. solani* (Hoitink et *al*., 1997; Fuchs, 2002, Fuchs and Larbi, 2004).

In both case, there is large variability within the product classes. This indicates that the management of the composting process is a major factor influencing the suppressive capacity of the composts.

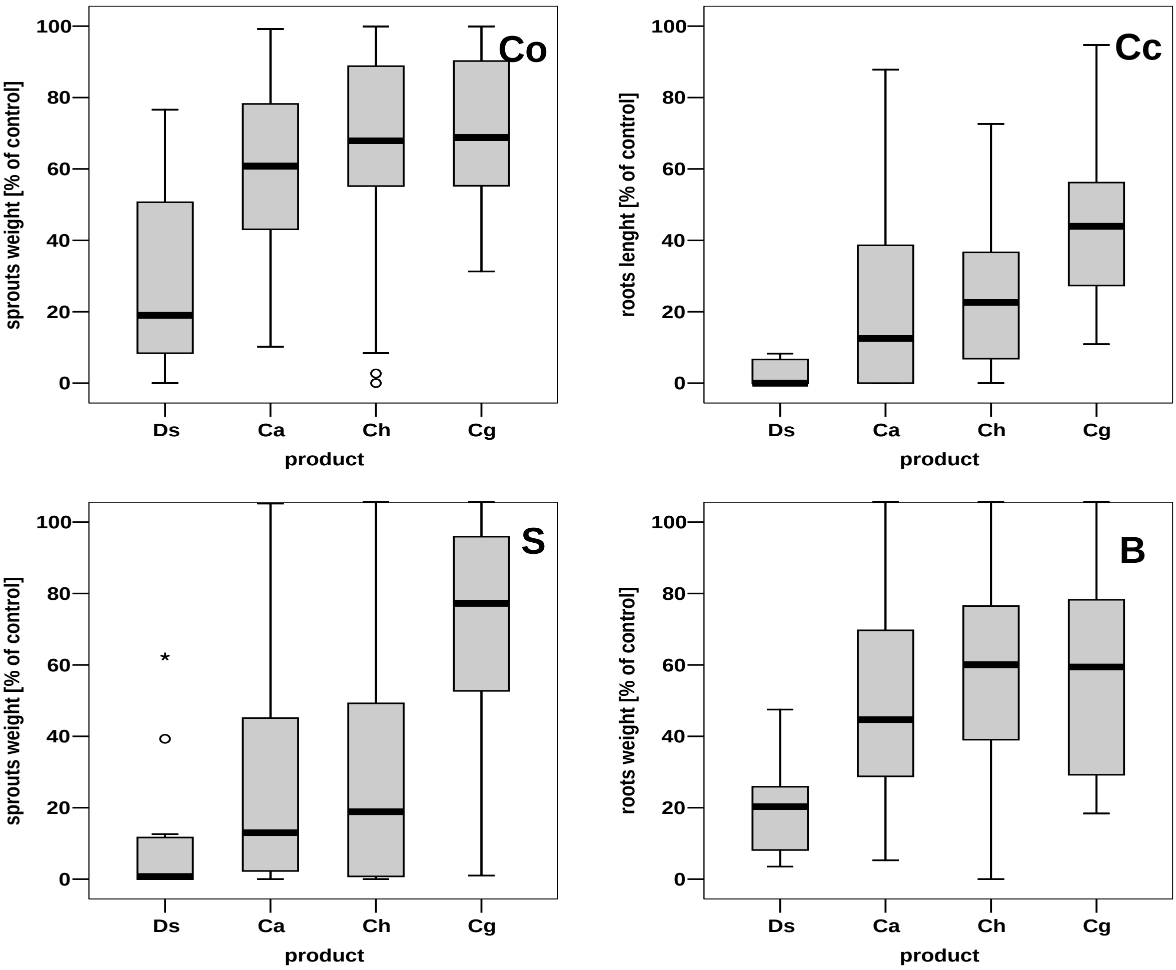

Figure 5 Phytotoxicity of Swiss composts for cress (Co and Cc), salat (S) and beans (B). The growth of the plants in pots filled with compost was compared with the growth of the plants in reference substrate (Co, S and B). Products were sampled according to ASCP Guidelines 2001 (Fuchs et al., 2001): Ds=digestate solid, Ca=compost for agriculture, Ch=compost for horticultural used, Cc=compost for covered cultures and private gardening.

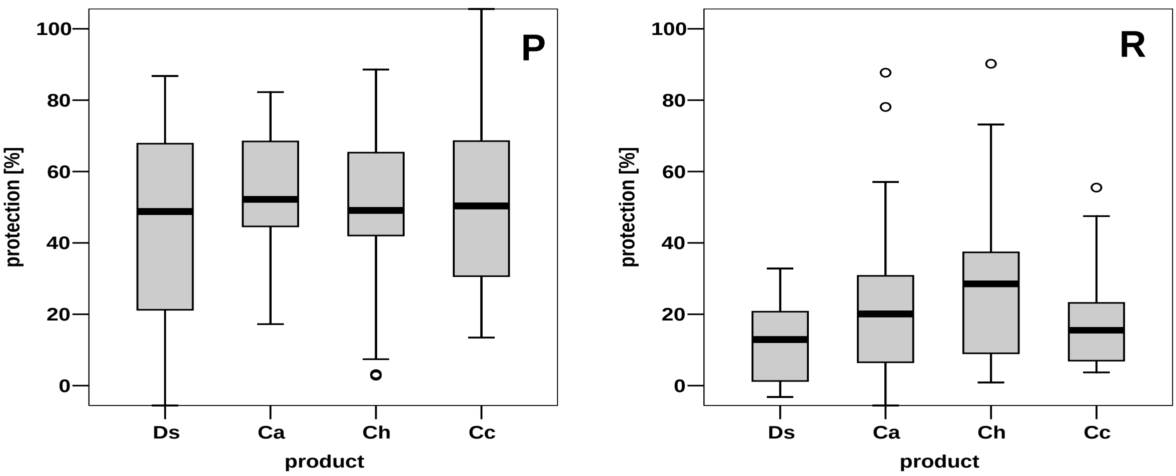

Figure 6 Capacitiy of Swiss composts to protect plants against soilborne diseases. P: protection from cucumber against *Pythium ultimum*; R: protection of basil against *Rhizoctonia solani*. Products sampled according to ASCP Guidelines 2001 (Fuchs et al., 2001): Ds=digestate solid, Ca=compost for agriculture, Ch=compost for horticultural used, Cc=compost for covered cultures and private gardening.

4 General discussion and outlook

In general, it was observed that the quality of the Swiss composts is good. No major problems were observed in any sample. One important reason for this is certainly that only source separated organic materials are composted. Nevertheless, the characteristics of the different digestates and composts vary in an important way. Some parameters like the nutrient contents, the heavy metals contents and the salinity are influenced principally by the materials of origin. Other parameters like the density, the organic matter, the enzymatic activities, the respirometric activity and the phytotoxicity are principally influenced by the maturity of the products. The nitrogen immobilization potential is affected by maturity, by the composition of the composted materials and by the management of the composting process. The major influence of the biological quality of the composts (phytotoxicity and suppressive potential) seems to be due to the management of the composting process.

The differences observed between the different composts indicate clearly that the choice of the right compost for the envisaged utilization is very important. The results confirm that the four product classes proposed in Switzerland make sense (solid digestate (Ds), compost for agricultural use (Ca), compost for horticultural use (Ch), compost for covered cultures and gardening (Cc)). They should be refined for some parameters, for example for the nitrogen immobilization potential. This is a very important parameter for the compost users, and this characteristic can show large variation especially in digestate and young composts. Field experiments carried out in the last two years show that the incubation tests presented here correlate very well with the performance of maize in the field (data not shown). More attention should be given to nitrogen immobilization, particularly when compost is used in spring.

A very important point demonstrated by this study is the fact that the compost producer plays a determinant role as manager of the composting process. Especially the biological quality of the compost is influence by the composting process. These characteristics differentiate composts from other fertilizers and soil amendments. To make use of the positive potentials of composts, it is important to optimize the composting process to obtain a quality product. This requires a broadening of the focus, to include not only heavy metal and nutrient contents, but also biological quality. This work clearly demonstrates the potential of compost. At present, this potential is utilized only to a very low extent in practice.

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Acknowledgments

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