Further studies in the nitrogen cycle of Surtsey, 1974—1976

By
Lars Eric Henriksson
Institute of Physiological Botany,
University of Uppsala,
S-751 21 Uppsala, Sweden
and
G. Alan Rodgers
Soils and Plant Nutrition Department,
Rothamsted Experimental Station,
Harpenden, Herts AL5 2JQ, England

INTRODUCTION

The volcanic island of Surtsey was formed by a series of eruptions during 1963—68. Since the eruptions ceased, colonization of the island by algae (Behre and Schwabe, 1970, Schwabe, 1972, 1974), bacteria and fungi (Henriksson and Henriksson, 1974a), lichens (Kristinsson, 1974), mosses (Magnusson and Fridriksson, 1974) and angiosperms (Fridriksson, 1975) is proceeding rapidly. A primary factor limiting the settlement and dispersal of the organisms may be the lack of utilizable nitrogen. Unfortunately there are few data on the initial mineral nitrogen contents of Surtsey soils. However, Ponnamperuma et al. (1966) determined the NH_4—N content of soil as 0—5 ppm soil and NO_3—N as 0—30 ppm soil. In 1972 Henriksson and Henriksson (1974b) determined NH_4—N as 60—70 ppm soil and NO_3—N as 0—10 ppm soil.

Various mechanisms could be responsible for the input of combined nitrogen to the island. Henriksson and Henriksson (1974b) have shown that organic nitrogen can enter Surtsey soil via the fixation of atmospheric nitrogen by blue-green algae and the mean value of 150 samples determined *in situ* in August 1972 was 13.74 ng nitrogen fixed per cm^2 and hour. The sea, rain, wind and animals may also transport organic nitrogenous material, either living or dead, to the island. Inorganic combined nitrogen may be deposited on Surtsey as NH_4 or NO_3 dissolved or suspended in rainwater. Also dry deposition of particulate ammonium or gaseous ammonia from the atmosphere may occur (Söderlund and Svensson, 1976). This deposited ammonia may be augmented by ammonia released from numerous steam vents on the island as volcanic activity has been suggested as an important source of atmospheric ammonia.

The aim of our present investigation was twofold: *First,* to compose and evaluate the various processes by which combined nitrogen may be added to Surtsey soils. *Second,* to obtain baseline-data on NH_4—N, NO_3—N and total N contents of soils from sites on the island, where different mechanisms of combined nitrogen input are operative, so that future studies can determine the importance of activities of the mechanisms involved in the nitrogen balance of Surtsey soil.

In 1974 (July 29 — Aug. 3) one of us (Henriksson) and in 1976 (Aug. 6—11) both of us visited Surtsey for field works and the following study is based on our results from these investigations.

MATERIAL AND METHODS

The methods and techniques used for collecting, analysing and cultivating the samples, according to the data recorded in Tables 1 and 2, are published by Henriksson and Henriksson (1974b). The acetylene reduction technique was used for the *in situ* determinations of the biological nitrogen fixation in the soil surface layers, and also potential bacterial nitrogen fixation was taken into consideration (Henriksson and Henriksson, 1978). However, the medium for *Thiobacillus denitrificans* was according to Postgate (1966) and as follows: NH_4Cl 0.5 g, $MgCl_2 \cdot 6H_2O$ 0.5 g, KH_2PO_4 2 g, $Na_2S_2O_5 \cdot 5H_2O$. 5 g, KNO_3 2 g, $NaHCO_3$ 1 g, $FeSO_4 \cdot 7H_2O$ 10 mg, tap water up to 1 l (pH 7.0).

Material from the localities in 1976 (Table 2 and Figure 2) has also been analysed in regard to the terrestrial microfauna by Hedin (1978).

The data recorded in Table 3 and 4 were based on the following methods. Soils were collected and stored in polythene bags prior to analysis. NH_4—N, NO_3—N and total N contents of soil were determined by the extraction and distillation

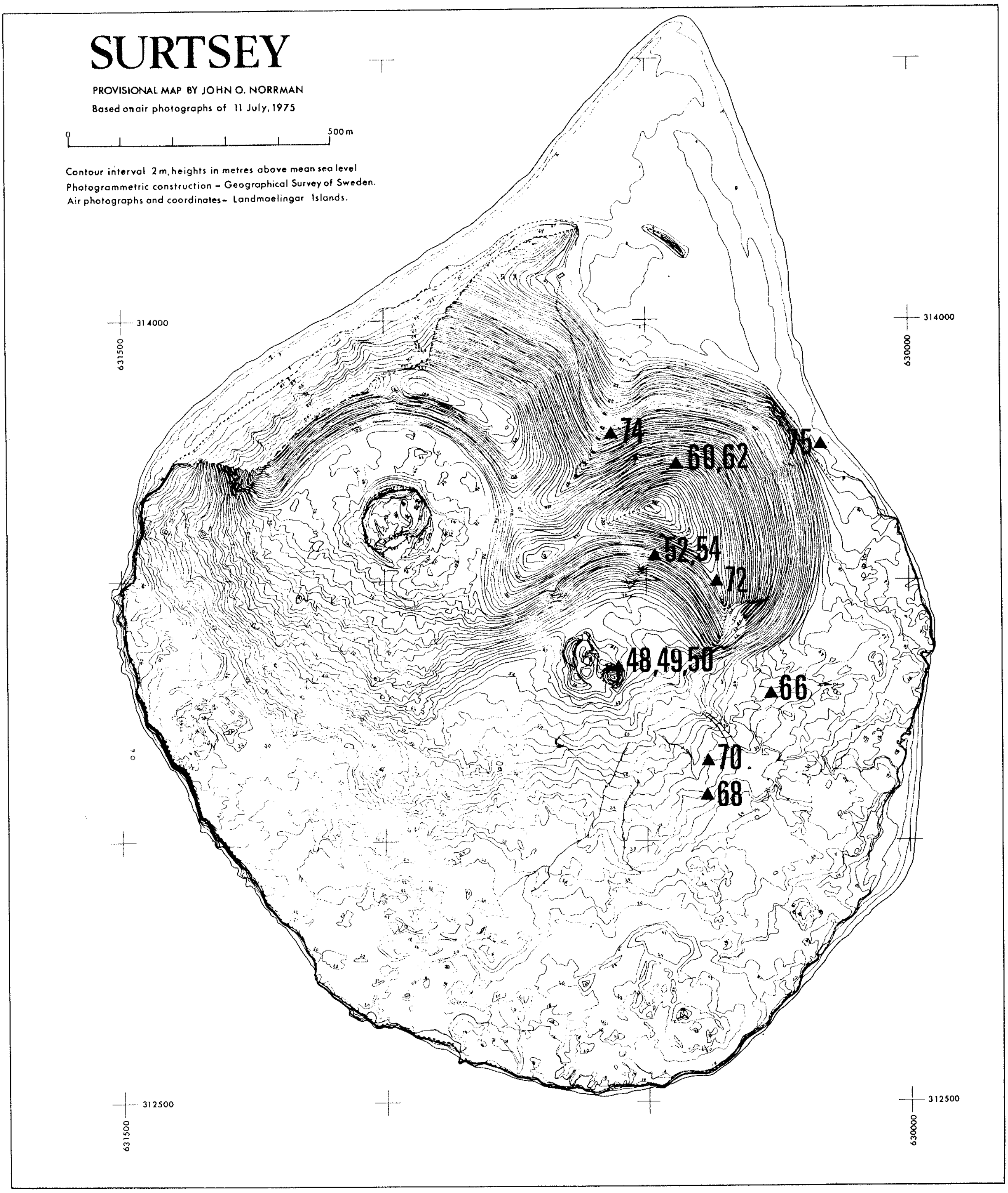
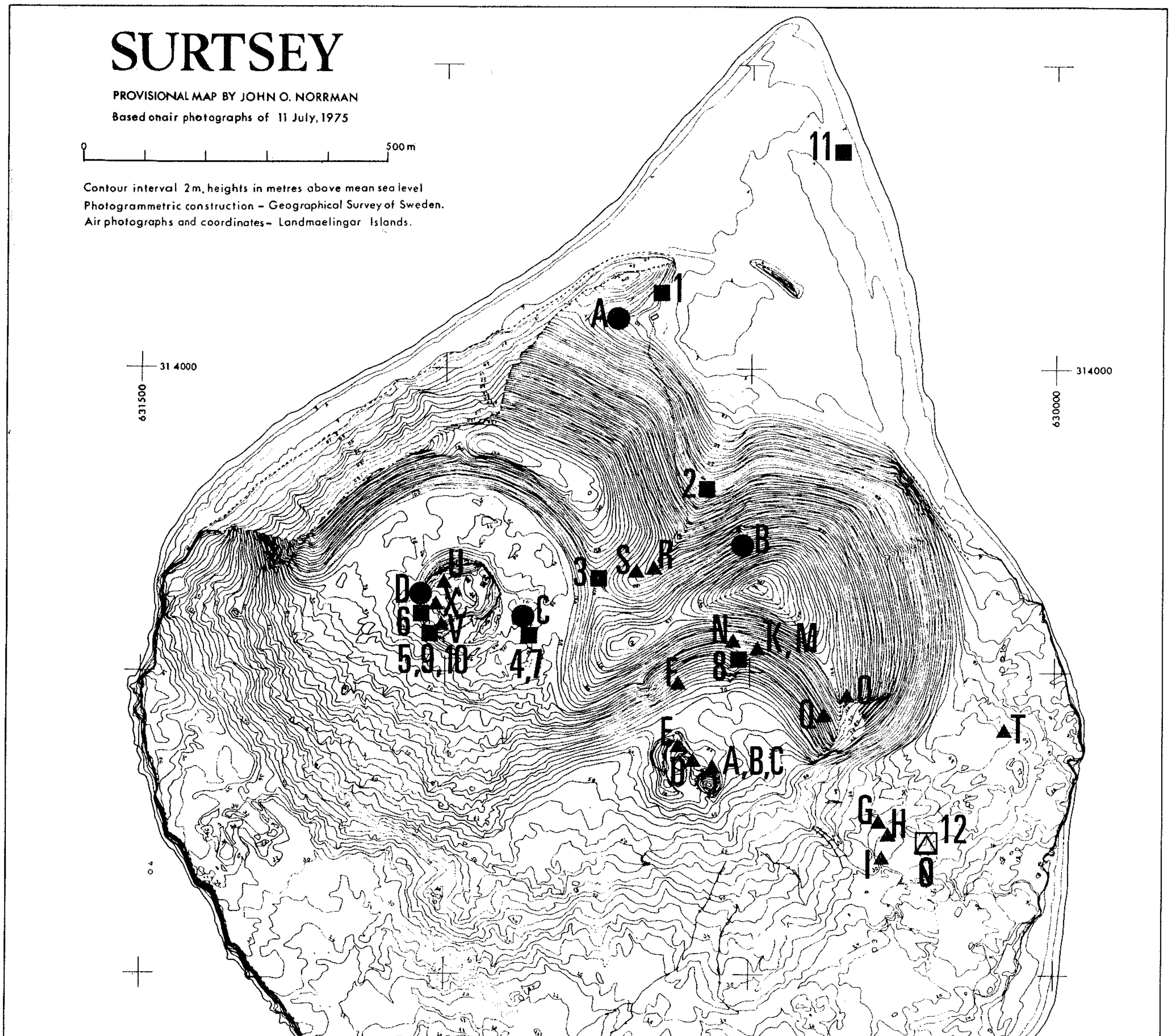


Figure 1. The symbols show the locations for samplings and the nitrogen fixing determinations *in situ* in 1974 and refer to Table 1. — Map of Surtsey by John Norrman, Uppsala.



Fugure 2. The locations for the samplings and analyses in 1976. The symbols ▲, ■, ● refer to Tables 2, 3, and 4, respectively. — Map of Surtsey by John Norrman, Uppsala.

procedures of Bremner (1965). Ammonia distillates were collected in 5% boric acid and analysed for ammonium by the indophenol technique of Rommers and Visser (1969).

Dry deposition of ammonia was calculated by exposing 12.5 cm diameter Whatman No. 41 filter papers to the air at various sites (Table 4). The papers were clamped in perspex frames and only one side was exposed to the air. After exposure the papers were stored in sealed polythene bags until return to the laboratory. The papers were dissolved in 5 ml 18M H_2SO_4 and the solution deluted to 30 ml with H_2O, then steam distilled for 3 minutes in a Markham distillation apparatus with 50% NaOH. The distillate was collected in 5% boric acid and analysed for NH_4—N.

Rainwater was collected in a rain gauge but the amounts collected during the field work period in 1976 were too small for analysis. Therefore figures for the nitrogen content of rain were taken from those of Miller (1913) for Vifilsstadir (Heimaey, Westman Islands) during 1911—1912. These figures may be underestimates due to increases in general atmospheric pollution since they were taken.

The distribution of lava and tephra areas on the island is analysed by Norrman et al. (1974), and their results have been taken into consideration.

RESULTS

The analytical results from the field seasons 1974 and 1976 are recorded in Tables 1—5 together with short descriptions and actual data of the localities investigated. The presence of the investigated microorganisms involved in the nitrogen cycle is also reported in Table 2 and the sites are plotted out in Figures 1 and 2 respectively.

The biological nitrogen fixation

All localities investigated *in situ* in 1974 and 1976 showed biological nitrogen fixation which could be referred to the activities of the frequent presence of the blue-green algae *Nostoc muscorum* Ag. and *Anabaena variabilis* Kütz. (Tables 1 and 2).

Table 1. The results of the nitrogen fixing determinations *in situ* in 1974 and the total—N content, pH and spec, conductance of the soil and a description of the localities studied. Location Nos refer to Fig. 1.

Table 1.

Sample location No.	ng N_2 fixed $cm^{-2}h^{-1}$ Mean of 9 samples	Total N mg/100 g dried soil	pH	Spec. conductance 20°C —10^{-4}	Description of the locations and temperature and light conditions at time of sampling and during the *in situ* experiments
48/74	4.6 ± 1.7	14.0	—	—	The south outside of the crater, 4 m from border. Light green lava. Water vapour. Soil temp. 38°C. 110.000 Lux.
49/74	2.8 ± 1.4	16.0	—	—	Crater border. Moist. Sparse young mosses. Soil temp. 29°C. 110.000 Lux.
50/74	12.2 ± 2.1	19.0	—	—	2 m from site 49, near steam vent. Soil temp. 48°C. 110.000 Lux.
52/74	6.0 ± 1.9	30.0	6.8	0.3	1.5 m from opening of the "Bell"-cave (according to G.H. Schwabe). Moist. Sparse moss cover. Soil temp. 22°C. 110.000 Lux.
54/76	5.3 ± 1.7	4.0	5.6	0.9	Right interior wall of the "Bell". Very moist. Moss-covered. Soil temp. 32°C. 450 Lux.
60/74	12.9 ± 2.5	10.0	7.9	0.3	Northern lateral crater of Surtur I. Moist. Green surface. Soil temp. 22°C. 68.000 Lux.
62/74	10.7 ± 1.4	11.0	7.9	0.3	East-side of lateral crater site 60. Slightly green lava soil. Soil temp. 22°C. 91.000 Lux.
66/74	12.7 ± 1.8	14.0	—	—	East-side of island about 30 m above sea level. Moist. Brown-yellow tephra. Soil temp. 17°C. 62.000 Lux.
68/74	7.5 ± 1.6	16.0	—	—	Lava field, south of Surtur I, 35 m above sea level. Moist. Brown--yellow tephra. Soil temp. 19°C. 59.000 Lux.
70/74	31.6 ± 1.9	16.0	—	—	About 50 m north site 68. Moist, brown-grey tephra. Soil temp. 19°C. 59.000 Lux.
72/74	13.5 ± 2.0	11.0	8.5	1.0	South-eastern slope of Surtur I, 120 m sea level. Moist, grey-brown lava. Soil temp. 22°C. 130.000 Lux.
74/74	27.5 ± 3.7	38.0	7.6	0.4	Pass between Surtur I and II. Moist. Soil temp. 16.5°C. 78.000 Lux.
75/74	17.4 ± 2.4	6.0	7.4	63.0	North-eastern slope-base of Surtur I, 10 m above sea level. Moist. Soil temp. 27°C. 110.000 Lux. Obviously contaminated by the sea.

Sample location No.	ng N_2 fixed $cm^{-2}h^{-1}$ Mean of 9 samples	Occurrence of					mg/1
		nitrogen fixing blue-green algae	*Azoto-bacter*	nitrifying organisms	denitrifying organisms	*Thiobacillus denitrificans*	NH
A/76	10.7 ± 1.1	*Anab. variabilis*	+	+	+	+	2.3
B/76	10.8 ± 3.5	*Nost. muscorum*	+	+	+	+	1.8
C/76	5.1 ± 1.8	*Nost. muscorum*	+	+	+	+	0.2
D/76	10.2 ± 1.7	Akinetes.	+	+	+	+	1.0
E/76	0.6 ± 0.2	*Anab. variabilis* *Nost. muscorum*	+	+	+	+	0.8
F/76	8.6 ± 2.0	*Nost. muscorum* Oscillarieae (*Schizothrix sp.?*)	+	+	+	0	5.3
G/76	6.0 ± 0.4	*Anab. variabilis*	+	+	+	+	0.5
H/76	12.4 ± 4.1	—	+	+	+	+	0.2
I/76	15.7 ± 1.8	*Nost. muscorum*	+	+	+	+	1.2
K/76	9.4 ± 0.8	*Nost. muscorum*	+	+	0	0	2.2
M/76	10.2 ± 1.1	*Nost. muscorum*	+	+	+	(+)	0.8
N/76	3.7 ± 0.5	—	+	+	+	0	2.6
O/76	0.9 ± 0.1	*Nost. muscorum*	+	+	+	0	1.5
R/76	1.3 ± 0.1	*Nost. muscorum*	+	+	+	(+)	2.9
S/76	0.2 ± 0.	*Nost. muscorum*	+	+	+	(+)	1.2
T/76	0.3 ± 0.1	—	+	+	+	+	1.6
U/76	44.8 ± 6.1	*Anab. variabilis*	+	+	+	+	1.2
V/76	56.9 ± 5.7	*Anab. variabilis*	+	+	+	+	0.
X/76	81.9 ± 12.8	*Anab. variabilis* *Nost. muscorum*	+	+	+	+	1.4
Ø/76	4.3 ± 1.1	*Nost. muscorum*	+	+	+	+	1.2

Table 2. The occurrence of some different types of microorganisms involved in the nitrogen cycle of Surtsey, the results of the nitrogen fixing a description of the localities studied in 1976. Location Nos refer to Fig. 2. and symbols ▲. Organisms present +, absent O.

Table 2

g dried soil					
NO3-N	Total-N	pH	Spec. conductance, 20°C ·10 −4	Humidity % above soil surface	Description of the locations and temperature and light conditions at time of sampling and during the *in situ* experiments
< 1	6.0	7.5	0.1	90.5	Crater border Surtur I. Sparse moss protonemata. Moist. Soil temp. 10°C. 50.000 Lux.
< 1	10.0	7.6	0.2	90.5	4 m from site A/76. Sparse moss protonemata. Moist. Soil temp. 11.5°C. 48.000 Lux.
< 1	10.0	7.6	0.2	90.5	12 m from site A/76 on outside slope. New moss protonemata. Soil temp. 16°C. 40.000 Lux.
< 1	13.0	7.2	0.1	101.0	Interior south-eastern slope Surtur I. 8 m from crater border. Surface blue-green. Some moss protonemata. Soil temp. 26°C. 26.000 Lux.
< 1	21.0	7.5	0.2	101.0	Next to site D/76 and of the same appearance. Soil temp. 33°C. 32.000 Lux.
7.2	15.0	6.1	0.7	100.0	The rocky knoll between the "Bell" (the cave according to G.H. Schwabe) and the southern lateral crater. Blue-green algal masses on the vertical, steaming site. Soil temp. 40—45°C. 20.000 Lux. (The highest soil temp. for Surtsey this visit was recorded here, 72°C).
< 1	16.0	7.5	0.1	92.0	Eastern lava field. *Elymus arenarius* area (Surtsey No. 74/75). Samples from surface close to the plants. Soil temp. 12°C. 55.000 Lux.
< 1	6.0	7.4	0.1	96.0	About 15 m from site G/76. Continous tuft of *Honkenya peploides* (Surtsey No. 73/440). Surface samples just under the plants. Soil temp. 11°C. 30.000 Lux.
< 1	9.0	7.8	0.1	94.5	About 50 m south site G/76 nest to lava blocks. 1—1.5 m^2 of soil with young species of the lichen *Stereocaulon* (rather common). Soil temp. 12°C. 38.000 Lux.
< 1	28.0	6.8	0.2	98.0	The "Bell", the interior left wall of the cave, 4 m from the entrance. Water leaking out. Wall greenish and occasionally mosses. Soil temp. 12°C. 8.000 Lux.
1.3	10.0	7.1	0.3	98.0	At the right side of the entrance of the "Bell". Soil greenish. Very moist. Soil temp. 16°C. 50.000 Lux.
3.8	16.0	7.9	0.7	100.0	About 15 m from the entrance of the "Bell" and about 10 m from a bigger steaming vent. Greenish soil and occasionally mosses. Soil temp. 18°C. 38.000 Lux.
< 1	10.0	8.2	0.2	90.0	South-eastern slope of Surtur I, about 100 m above the sea level. Signs of erosion, greenish surface. Soil temp. 16°C. 40.000 Lux.
< 1	10.0	7.6	0.2	97.0	The upper part of the passage between the head craters. Soil grey. Moist. Soil temp. 11°C. 32.000 Lux.
< 1	7.0	7.4	0.2	97.0	About 3 m from site R/76. Blackish soil. Soil temp. 11°C. 30.000 Lux.
< 1	8.0	7.2	0.3	93.5	The shore plateau at the eastern slope of Surtur I, about 20 m above sea level. The blueish lava sand contaminated by the sea. Colony of *Rissa tridactyla* L. (more than 200 kittywakes). Soil temp. 10°C. 36.000 Lux.
< 1	15.0	7.0	0.5	92.0	The southern part of the crater bottom of Surtur II. Continuous well-developed areas with mosses. Moist. Soil temp. 13°C. 39.000 Lux.
< 1	13.0	7.2	0.1	88.5	About 15 m from site U/76 and similar. Moist. Soil temp. 16.5°C. 45.000 Lux.
< 1	17.0	7.2	0.2	84.5	Southern part of the crater bottom next to sites U/76 and V/76 and similar. Soil temp. 14.5°C. 40.000 Lux.
< 1	7.0	7.2	0.3	89.5	The investigation square (6×6 m), marked out by the Swedish Bio--Geo-Group, Uppsala Aug. 8, 1976. (Ref. map point 1:4 p. 611, John Norrman, Uppsala).

terminations *in situ*, and the chemical analyses of the soil, and

The total number of the *in situ* determinations from Surtsey 1972 (Henriksson and Henriksson, 1974b), 1974 and 1976 are collated in Table 5 and the average values from the different seasons indicate that the biological nitrogen fixation seems to be of the same order during this time.

These data from Surtsey and those of Henriksson et al. (1972b) and Henriksson and Henriksson (1974b) correspond well to the results published by Englund (1976, 1978). Thus she reports about the same values from the new lava fields on Heimaey in 1974 and 1976. Crittenden (1975) has also obtained results of interest in regard to nitrogen fixation by lichens on glacial drift at Sólheimajökull, Iceland.

The most striking observation will be the low nitrogen fixing capacities for the Icelandic virgin soils, both on Surtsey and on Heimaey and on the main island as well in comparison to e.g. many Swedish soils (Henriksson, 1971, Henriksson et al., 1972a, 1975 and Granhall, 1975). In the Swedish soils a biological, ecological balance is already established and this balance is still missing in the new Icelandic soils.

However, at present the nitrogen fixing activities of the blue-green algae must be of major importance for the nitrogen input and economy on Surtsey as even a small input of nitrogen to an ecosystem characterized as nitrogen deficient must be of hithest importance. This fact is of fundamental significance for the primary stages of soil formation (Schwabe, 1963, Harley, 1970, Shtina and Nekrasova, 1971, Vlassak, 1972).

The heterotrophic bacterium *Azotobacter* was registered for the first time on Surtsey in 1976 and was frequent occurring (Table 2) and also the chemoautotrophic bacterium *Beggiatoa* was found in about one third of the localities investigated (Henriksson and Henriksson, 1978). Any nitrogen fixing activities in the Surtsey soil by these organisms has, however, not yet been observed.

Nitrification and denitrification organisms in Surtsey in 1976

The occurrence of nitrifying and denitrifying organisms on Surtsey was demonstrated in 1972 by Henriksson and Henriksson (1974b). Further studies were continued in 1976 (Table 2) and the results showed the frequent occurrence of organisms representing these significant activities in the nitrogen cycle. In 1976, however, the chemoautotrophic bacterium *Thiobacillus denitrificans* was also registered in most localities investigated.

As far as can be judged from the observations and results recorded nitrification may be assumed to occur on Surtsey and, although bacteria ca-

Table 3

Sample location No.	mg / 100 g dried soil			Soil type	Description of the locations
	NH_4—N	NO_3—N	Total-N		
1/76	0.32	0.03	1.06	Tephra	Soil under *Honkenya peploides* (L.) Ehrh. colony.
2/76	0.27	0.06	0.75	Tephra	On bare hillside 100 m above sea level.
3/76	0.35	0.03	0.45	Tephra	Top of slope 125 m above sea level.
4/76	0.13	0.04	0.25	Lava	Steam vent, near the opening.
5/76	0.37	0.03	0.52	Lava	Soil with mosses near Surtur II.
6/76	0.20	0.05	0.44	Lava	Soil without mosses near Surtur II.
7/76	0.27	< 0.01	2.53	Lava	Steam vent with visible blue-green algae.
8/76	0.33	0.34	3.44	Tephra	Soil from the "Bell"-cave with blue- green algae.
9/76	0.38	0.04	0.89	Lava	Surface (1—2 cm) soil near Surtur II.
10/76	0.24	0.04	0.42	Lava	Soil at 20—25 cm near Surtur II.
11/76	6.10	0.18	14.40	Lava	Soil from boulder zone on shore with bird excreta.
12/76	0.20	0.06	0.68	Lava	The investigation square, marked out by the Swedish Bio-Geo-Group, Uppsala, Aug. 1976. (Ref. map point 1:4 p. 611, John Norrman, Uppsala).

Table 3. Analyses of NH_4—N, NO_3—N, and total-N, and a description of the localities studied in 1976. Location Nos refer to Fig. 2 and symbols ■.

Table 4

Site and description	Height above sea level (m)	Time papers exposed (h)	Deposition ng $cm^{-2}h^{-1}$	Deposition kg ha^{-1} ann^{-1}
A. On clifftop.	10	73	2.91	2.6
B. On the north-eastern slope.	100	72	3.30	2.9
C. At a fumarole opening.	100	19.8	16.45	14.4
D. At Surtur II, near steam vent.	100	19.3	59.74	53.3

Table 4. NH_4/NH_3 dry deposition at different sites on Surtsey in 1976. Location characters refer to Fig. 2 and symbols ●.

pable of denitrification are present, it is doubtful if denitrification can generally occur due to the absence of organic carbon or reduced sulphur compounds necessary for energy formation and growth, and also the well-drained nature of Surtsey soil.

The chemical soil analysis and the air-borne nitrogen deposition on Surtsey

The chemical soil analyses both from 1974 and 1976 indicate an increasing total nitrogen content of the Surtsey soils in comparison to earlier available data (Ponnamperuma et al., 1967, Henriksson and Henriksson, 1974b). Increasing values were specially recorded in respect to NH_4—N and organic nitrogen (Tables 2 and 3).

In respect to the in 1976 registered and calculated air-borne NH_4/NO_3 depositions on Surtsey (Table 4) the nitrogen contributions to the soil will be between 2.9—59.7 ng N $cm^{-2}h^{-1}$. This actual nitrogen deposition on Surtsey must however be divided into two main sources: one generally occurring (A and B in Table 4) and one greatly enlarged just in the vicinity of the fumaroles and steam vents (C and D in Table 4) on the island.

The determinations of the specific conductance (Table 1 and 2) indicate an increased inclusion of inorganic matter in all localities investigated (cp. Henriksson and Henriksson, 1974b). This contribution in the upper layers of the soil has obviously come from the sea.

The pH-values of the soils investigated in 1974 and 1976 represent neutrality or small divergences from that (Tables 1 and 2). However the results show a clear tendency of the soils becoming more alkaline in comparison to the earlier available data from 1965 pH 4.5—6.8 (Ponnamperuma et al., 1967), 1970 pH 5.7—7.0 (Schwartz and Schwartz, 1972), 1972 pH 6.6—6.8 (Henriksson and Henriksson, 1974b).

During dry weather in 1974 and 1976 several restricted areas (up to 1—2 m^2) were covered with noticeable and rather thick surface layers of crystals. These spots were especially noticeable on the slopes of Surtur I and II. Analyses have shown, that these crystals were principally built up by chlorides of sodium, magnesium and potassium but sulphates were not found (Location Ø/76, Figure 2). It seems possible that these crystal spots are the result of leaching processes.

Some observations about the water conditions on Surtsey and the water and temperature factors according the biological nitrogen fixation of the blue-green algae

Any annual mean values of the precipitation and temperature on Surtsey are not recorded. However, from the seasonal data and calculations by Sigtryggsson (1968) an annual mean value of the precipitation can be estimated to about 1000 mm from the basis of the annual long-term values from Stórhöfdi Meterological Station, Westman Islands (Vedráttan, 1944—76). The precipitation variability may be less than 10% of the longterm average (Morales, 1977) and the long-term records from Stórhöfdi also indicate a rather uniform distribution of the precipitation during the year.

The annual mean temperature is recorded at Stórhöfdi to be +5.4°C for the period 1931—1960 (cp. +5.7°C for Uppsala) and there will probably be small differences between Stórhöfdi and Surtsey.

In regard to temperature conditions it has been demonstrated that the blue-green algae have a remarkable nitrogen fixing capacity at low and at sub-zero temperatures (Kallio et al., 1972, Englund and Meyerson, 1974).

During the period Aug. 6—11, 1976 the recorded precipitation on Surtsey was 24 mm. The air humidity values just over the soil surface varied during the same time between 84.8—101.0% and the supersaturated values could be related to effects from steaming vents. The air temperature during daytime was for the same time 10.5—15.0°C, however two shorter periods of 18.0 and 15.5°c respectively were observed.

Shtina (1972) reported that the soil moisture was one of the main conditions that determined the distribution and degree of nitrogen fixation by blue-green algae, and optimum activities were observed at 80—100% of humidity.

In laboratory experiments under controlled conditions it was shown, that the effect of soil humidities lower than 40% reduced the nitrogen fixation by *Nostoc sp.* and *Anabaena sp.* in an obvious way even though the air humidity in the experimental flasks was more or less saturated, and at 30% soil humidity the nitrogen fixation was only one third of that at 40% humidity. These results (unpublished) and the data above, however emphasize favourable water conditions for algal nitrogen fixing activities on Surtsey.

DISCUSSION

Due to the very low content of organic matter in Surtsey soils the decomposition rate must be very low and in such environments the biological nitrogen fixation must be of especial importance. Besides nitrogen fixation the atmospheric fallout represent the second major nitrogen input to the island. This is in accordance with the opinion of Alexander (1975), who found nitrogen fixation and rain being the two major nitrogen inputs to the soil in polar and subpolar regions.

Even in developed and cultivated soils the mineral factor of the solid phase dominates and only a smaller part of the total mass represents organic matter. The fertility of a soil is increased by an increase in organic matter content due to its water holding capacity, structure-building function and absorbing properties (Pearson, 1967), and the latter fact is specially true in respect to NH_4—N. In that way the fertility of the Surtsey soil generally seen will therefore be low on account of its extremely low content of organic matter, which means a more or less absence of the ability to absorb and store NH_4—N.

The NO_3—N is known to leach out rapidly in soils (Overrein, 1969) and in the sandy soils of Surtsey the leaching effect may be total.

The annual wet deposition of nitrate and ammonia compounds can be calculated as 0.1 g NO_3—N $m^{-2}ann^{-1}$ and 0.1 g NH_4—N $m^{-2}ann^{-1}$ maximum respectively in the Icelandic regions (Söderlund, 1977). However, if influences of man's activities are left out on account, the background value of the total nitrogen fallout can be estimated to be about 0.1 g N $m^{-2}ann^{-1}$.

Owing to the above facts and the abundant rainfall on Surtsey a very low accumulation of nitrogen might be referred to the atmospheric fallout. Anyhow some parts of this particular nitrogen delivery can be assimilated by the present plants or transferred in the nitrification and denitrification processes on the island.

The nitrogen analyses from the period 1965—1976 indicate a distinct sign of enrichment of organic and NH_4—N in the lava soil of Surtsey. The determinations of the biological nitrogen fixation *in situ* on the island indicate that this activity is of fundamental, ecological importance for the nitrogen economy of the island. The average values of the total number of determinations *in situ* of the nitrogen fixation from Surtsey in 1972, 1974 and 1976 respectively are estimated and recorded in Table 5 and they indicate, that the biological nitrogen fixation on Surtsey can be regarded as a constant nitrogen deliverer to the lava soil. The favourable external factors as humidity, annual mean temperature and pH existing on Surtsey for the activities of the present nitrogen fixing blue-green algae emphasize these observations.

Englund (1977, 1978) has reported the same experiences from the new lava fields on Heimaey (Westman Islands) formed in 1973. However her average value from 1976 was about half those from Surtsey, which may be referred to differences in ages of the soils.

The biological nitrogen fixation on Surtsey is known to be due to the frequent occurrence of blue-green algae (Schwabe, 1974, Henriksson et al., 1972, Henriksson and Henriksson, 1974b). These algal pioneers frequently exist free-living, in symbiosis with lichens and in associations with mosses on the island. Of special interest is the moss association, a connection known for a long-

Table 5. Mean values of the determinations *in situ* of the nitrogen fixation by blue-green algae on Surtsey in 1972, 1974 and 1976. The data in 1972 from Henriksson and Henriksson (1974b).

Table 5

Field season	Number of locations	Number of analyses	Biological N-fixation, ng N_2 cm $^{-2}h^{-1}$	
			Range	Mean value
1972	13	150	0.2—64.5	13.7 ± 1.9
1974	13	150	2.8—31.6	12.8 ± 2.8
1976	20	200	0.2—81.9	14.7 ± 1.2

time (e.g. Richter, 1907) which has been brought to the fore again on Surtsey and Heimaey by Schwabe (1974), Rodgers and Henriksson (1976) and Englund (1977a,b) and this association can explain the very early colonization and rapid distribution of moss plants on these new lava territories.

The pH of the Surtsey soils have gradually become more alkaline, which indicates a stimulation both in growth and nitrogen fixing activity of the blue-green algae, as the optimum ranges are pH 7.0—8.5 and pH. 7.0—7.5 respectively (Fogg et al., 1973). More acid conditions inhibit both growth and the nitrogenase activity. This is also of especial interest in the case of *Azotobacter,* as this organism is principially only found and established in soils at pH 6.5 or more.

The frequent occurence of *Azotobacter* in the Surtsey soil, recorded for the first time in 1976, will give new impetus to the nitrogen fixing processes since associated growth of *Azotobacter* with other organisms, including blue-green algae and protozoa, stimulates the nitrogen fixation (Bjälfve, 1963, Jensen and Holm, 1975, Henriksson, 1977).

The nitrogen deficiency in Surtsey soils for the development of higher plants has initially been demonstrated by Henriksson (1976) in laboratory experiments. However, this nitrogen deficiency on Surtsey might perhaps be eliminated by nitrogen fixation in the rhizosphere of the plants by e.g. *Azotobacter* or *Spirillum sp.* (Döbereiner, 1975, 1977, Smith et al., 1976).

Nitrification processes are nowadays generally occurring on Surtsey. Nitrifying organisms, including *Nitrosomonas* and *Nitrobacter,* are found everywhere on the island. The denitrifier *Thiobacillus denitrificans* is frequently observed in the lava soil in 1976. Stationary organisms on the island are species of bacteria, algae, actinomycetes, terrestrial fungi, mosses, lichens, higher plants, protozoa and insects. These facts indicate, that a representative part of the nitrogen cycle is already functioning on Surtsey. The different parts of the cycle may however still be suppressed (e.g. denitrification) in respect to the virgin conditions and the hitherto limiting biological development on the island. In that way genuine humus protein is still lacking, which in a common soil is of great importance for the nitrogen economy and balance of the biotype.

Further studies will determine whether or not the soil NH_4—N and NO_3—N levels will increase further with time or if they have reached an equilibrium. The organic levels in Surtsey soils are very low, e.g. compared with soil at Rothamsted (England), which has been under grass for 200 years, where the organic nitrogen content is 2800 ppm organic nitrogen. However, there is already a distinct increased level of organic nitrogen on localities containing blue-green algae and again further studies will establish the amounts of organic nitrogen they contribute to the soil and allow comparisons to be made with estimated nitrogen fixing rates.

ACKNOWLEDGEMENTS

The authors are indebted to Dr. Elisabet Henriksson, University of Uppsala, for valuable critisism and stimulating discussions. We are also grateful to Prof. Nils Fries, Head of the Institute of Physiological Botany, University of Uppsala, for his interest and provision of facilities. The fieldwork was sponsored by the *Swedish National Science Council* and by the *Surtsey Research Society.*

ABSTRACT

The relevant components of the nitrogen cycle of Surtsey are described and evaluated, due to the importance of combined nitrogen in the continued development of the island's soil and it's biology. The biological nitrogen fixation by the frequently present blue-green algae, determined *in situ* by using the acetylene reduction technique, is found to be of major importance for the nitrogen input to the Surtsey soil. In addition, NH_4—N and NO_3—N, washed from the atmosphere by rain augment soil nitrogen, as well as dry atmospheric deposition of NH_4—N, determined in higher concentrations around the fumaroles in certain localities on the island. Much of the inorganic nitrogen may be lost due to the presence of nitrifying bacteria and the welldrained soil from which NO_3—N can easily leach. It is unlikely, at yet, that denitrification generally occurs, though organisms involved in this part of the nitrogen cycle are frequently identified on Surtsey, as soils are well aerated and still lack utilizable reserves of organic carbon. However, in 1976 the chemoautotrophic bacterium *Thiobacillus denitrificans* was found to be frequently occurring in the Surtsey soil.

References

Alexander, V.A., 1975: Nitrogen fixation by blue-green algae in polar and subpolar regions. — In Nitrogen fixation by free-living microorganisms. IBP Vol. 6 (W.D.P. Steward, Ed.). Cambridge University Press, Cambridge. 471 pages.

Behre, K. and Schwabe, G.H., 1970: Auf Surtsey/Island im Sommer 1968 nachgewiesene nicht marine Algen. — Schr. Naturw. Ver. Schlesw.-Holst. Sonderband: 31—100.

Bjälfve, G., 1962: Nitrogen fixation in cultures of algae and other microorganisms. — Phys.Plant. 15: 122—129.

Bremner, T.M., 1965: In Methods of soil analysis II, Chapt. 83—84. — Agronomy Series, American Society for Agronomy, Madison Wisconsin, No. 9.

Crittenden, P.D., 1975: Nitrogen fixation by lichens on glacial drift in Iceland. — New Phytol. 74:41—49.

Döbereiner, J., 1977: Biological nitrogen fixation in tropical grasses — possibilities for partial replacement of mineral N fertilizers. — Ambio 6:174—177.

Döbereiner, J. and Day, J.M., 1975: Nitrogen fixation in the rhizosphere of tropical grasses. — In Nitrogen fixation by free-living microorganisms. IBP Vol. 6 (W.D.P. Stewart, Ed.). Cambridge University Press, Cambridge. 471 pages.

Englund, B., 1976: Nitrogen fixation by free-living microorganisms on the lava field of Heimaey, Iceland. — Oikos 27:428:432.

Englund, B., 1977: Studies on N_2-fixation by free-living and symbiotic blue-green algae using the acetylene reduction technique. — Acta Univ. Ups. No. 430 (Abstr. of Diss.). 45 pages.

Englund, B., 1978: Algal nitrogen fixation on the lava field of Heimaey, Iceland. — Oekologia (In press.)

Englund, B. and Meyerson, H., 1974: In situ measurement of nitrogen fixation at low temperatures. — Oikos 25:283—287.

Fogg, G.E., Stewart, W.D.P., Fay, P. and Walsby, A.E., 1973: The blue-green algae. — Acad. Press, London. 459 pages.

Fridriksson, S., 1975: Surtsey. — Butterworths, London. 198 pages.

Granhall, U., 1975: Nitrogen fixation by blue-green algae in temperate soils. — In Nitrogen fixation by free-living microorganisms. IBP Vol. 6 (W.D.P. Steward, Ed.). Cambridge University Press, Cambridge. 471 pages.

Harley, J.L., 1970: Importance of microorganisms to colonising plants. — Trans. Bot. Soc. Edinb. 41:65—70.

Hedin, H., 1978: On the terrestrial microfauna of Surtsey during the summer of 1976 with special reference to the ciliates. — Surtsey Research Progress Report 8: 47—50.

Henriksson, E., 1971: Algal nitrogen fixation in temperate regions, — Plant and Soil, Spec. vol. Biological nitrogen fixation: 415—419.

Henriksson, E., 1977: Physiological aspects on blue-green algae in association with other plants in soil. — Prof. R.N.Singh's Commemoration Volume (S.P. Singh, Ed.) Benares. (In press.)

Henriksson, E., Englund, B., Hedén, M.B. and Was, I., 1972,a: Nitrogen fixation in Swedish soils by blue-green algae. — In Taxonomy and biology of blue-green algae. (T.V. Desikachary, Ed.). Univ. Madras. 591 pages.

Henriksson, E., Henriksson, L.E. and Pejler, B., 1972,b: Nitrogen fixation by blue-green algae on the island of Surtsey, Iceland. — Surtsey Research Progress Report 6:66—68.

Henriksson, E., Henriksson, L.E. and DaSilva, E.J., 1975: A comparison of nitrogen fixation by algae of temperate and tropical soils. — In Nitrogen fixation by free-living microorganisms. IBP Vol. 6 (W.D.P. Stewart, Ed.). Cambridge University Press, Cambridge. 471 pages.

Henriksson, E. and Henriksson, L.E., 1978: The bacteria *Azotobacter, Beggiatoa,* and *Desulfovibrio* in the Surtsey soil. — Surtsey Research Progress Report 8: 28—30.

Henriksson, L.E., 1976: Effects of nitrogen, phosphorus, and potassium to Surtsey lava soils on the growth of a test plant (*Avena sativa,* L)- Acta Bot. Islandica 4:36—43.

Henriksson, L.E. and Henriksson, E., 1974,a: Occurrence of fungi on the volcanic island of Surtsey, Iceland. Acta Bot. Islandica 3:82—88.

Henriksson, L.E. and Henriksson, E., 1974,b: Studies in the nitrogen cycle of Surtsey in 1972. — Surtsey Research Progress Report 7:36—44.

Jensen, V. and Holm E., 1975: Associative growth of nitrogen-fixing bacteria with other microorganisms. — In Nitrogen fixation by free-living microorganisms. IBP Vol. 6 (W.D.P. Stewart, Ed.). Cambridge University Press, Cambridge. 471 pages.

Kallio, P., Suhonen, S. and Kallio, H., 1972: The ecology of nitrogen fixation in *Nephroma arcticum* and *Solorina crocea.* — Report of Kevo Subartic Research Station 9:7—14.

Kristinsson, H., 1974: Lichen colonization in Surtsey 1971—1973. — Surtsey Research Progress Report 7:9—16.

Magnusson, S. and Fridriksson, S., 1974: Moss vegetation on Surtsey in 1971 and 1972. — Surtsey Research Progress Report 7:45—57.

Miller, N.H.J., 1913: The composition of rain water collected in the Hebrides and in Iceland. — J. Scot. Met. Soc. 16:141—158.

Morales, C., 1977: Rainfall variability — a natural phenomenon. — Ambio 6:30—33.

Norrman, J., Calles, B. and Larsson, R.Å., 1974: The geomorphology of Surtsey Island in 1972. — Surtsey Research Progress Report 7:61—71.

Overrein, L.N., 1969: Lysimeter studies on tracer nitrogen in forest soil. II. Comparative losses of nitrogen through leaching and volatilization after addition of urea-, ammonium-, and nitrate N^{15}. — Soil Sci. 107:149—159.

Pearson, L.C., 1967 Principles of agronomy. — Reinhold Publ. Corp., New York. 434 pages.

Ponnamperuma, C., Young, R.S. and Caren, L.D., 1967: Some chemical and microbiological studies of Surtsey. — Surtsey Research Progress Report 3:70—82.

Postgate, J.R., 1966: Media for sulphur bacteria. — Laboratory Practice 15:1239—1244.

Richter, O., 1907: Die Bedeutung der Reinkultur. — Verlag von Gebrüder Borntraeger, Berlin. 128 pages.

Rodgers, G.A. and Henriksson, E., 1976: Associations between the blue-green algae *Anabaena variabilis* and *Nostoc muscorum* and the moss *Funaria hygrometrica* with reference to the colonization of Surtsey. Acta Bot. Islandica 4:10—15.

Rommers, J.P. and Visser, J., 1969: Spectrophotometric determination of micro amounts of nitrogen as indophenol. — Analyst. 94:653—658.

Schwabe, G.H., 1963: Blaualgen der phototrophen Grenzschicht. (Blaualgen und Lebensraum VII.) — Pedobiologia 2:132—152.

Schwabe, G.H., 1972: Blue-green algae as pioneers on postvolcanic substrate (Surtsey/Iceland). — In Taxonomy and biology of blue-green algae. (T.V. Desikachary, Ed.). Univ. Madras. 591 pages.

Schwabe, G.H., 1974: Nitrogen fixing blue-green algae as pioneer plants on Surtsey 1968—1973. — Surtsey Research Progress Report 7:22—25.

Schwartz, W. and Schwartz, A., 1972: Geomikrobiologische Untersuchungen. Besiedelung der Vulkaninsel Surtsey mit Mikroorganismen. — Zeitschr. f. Allg. Mikrobiol. 12:287—300.

Shtina, E.A., 1972: Some peculiarities of the distribution of nitrogen-fixing blue-green algae in soils. — In Taxonomy and biology of blue-green algae. (T.V. Desikachary, Ed.). Univ. Madras. 591 pages.

Shtina, E.A. and Nekrasova, K.A., 1971: The direct and indirect contribution of soil algae to the primary production of biocoenoses. — Int. Nat, de la Recherche Agronomique, Paris. 71:37—45.

Sigtryggsson, H., 1968: Preliminary report on meterological observations in Surtsey 1967. — Surtsey Research Progress Report 4:167—170.

Smith, R.L., Bouton, J.H., Schank, S.C., Quesenberry, K.H., Tyler, M.E., Milam, J.R., Gaskins, M.H. and Littell, R.C., 1976: Nitrogen fixation in grasses inoculated with *Spirillum lipoferum.* — Science 193:1003—1105.

Söderlund, R., 1977: NO_x pollutants and ammonia emissions — a mass balance for the atmosphere over NW Europe. — Ambio 6:118—122.

Söderlund, R. and Svensson, B.H., 1976: The global nitrogen cycle. — In Nitrogen, Phosphorus and Sculphur — Global Cycles. (Svensson, B.H. and Söderlund, R., Eds.). Scope Rep. 7. Ecol. Bull., Stockholm. 22:23—74.

Vlassak, K., 1972: Biologische Stikstoffixatie (Biological nitrogen-fixation) (In Dutch). — Agricultura 4:4—52.

Vedráttan, 1944—1976: Meterological Bulletin, Reykjavik.