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Soil and Fertilizer Nitrogen Dynamics and Grass Yield Changes of Meadows in Cool-Temperate Japan

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Abstract

The relationship among the changes of grass yield with the year after establishment, the uptake of fertilizer nitrogen, and soil nitrogen release in old meadows was studied from the viewpoint of decomposition of accumulated organic residues on the surface layer. Grass yield did not decline with the increase in the meadow age after the establishment under optimum fertilizer nitrogen application. However, when fertilizer nitrogen application was insufficient, grass yield of old meadows especially of those more than 9 years old decreased. The decrease resulted from the marked decrease in the first cutting yield of these old meadows. In such meadows, both the uptake of applied fertilizer nitrogen and release of soil nitrogen of the first cutting stage play an important role in maintaining the grass yield. These results were attributed to the large accumulation of organic residues on the surface layer and large C/N ratio. Immobilization of fertilizer nitrogen increased with the accumulation of organic residues, and the release of immobilized nitrogen decreased in the first growth period during which the soil temperature remained cool. Also, soil nitrogen mineralization potential (N01) of rapid release organic nitrogen decreased and apparent activation energy value (Ea1) increased with the increase of the meadow age. The sum of the second and the third cutting yields decreased due to the small amount of precipitation from July to August. This tendency was clearly observed in old meadows, due to the decrease in the decomposition of accumulated organic residues on the surface. There were no significant differences in the amount of total nitrogen in the 0 to 15 cm layer between a newly established meadow and a 15 years old meadow, although the distribution of nitrogen in the top 5 cm layer and 5 to 15 cm layer changed with the ageing of the meadow.

Discipline: Soils, fertilizers and plant nutrition/ Agricultural environment
Additional key words: fertilizer nitrogen efficiency, precipitation

Introduction

It is generally recognized that the grass yield of meadows begins to decrease 2 or 3 years after establishment[6,12], mainly due to the change in the botanical composition, especially through the disappearance of legumes resulting from inadequate fertilizer application and meadow utilization[7]. The decrease can also be attributed to the changes in the soil chemical and physical conditions by leaching of soil exchangeable cations such as Ca^{2+} and Mg^{2+} applied as potentially acid fertilizer[3], and by the compaction of the surface layer of grassland soil by harvesting machines[11]. Especially, acidification of the surface layer of grassland soil results in the inhibition of phosphate uptake by grasses[3], decline of soil microbial activity[1] and decrease of mineralization of soil organic nitrogen[8]. However, it is also recognized that no decline of grass yield with the ageing of meadow is observed under adequate fertilizer nitrogen application[4].

The differences in the results reported in previous papers[4,6,12] suggest that the amount of soil nitrogen released changes with meadow ageing. There are many sources of soil nitrogen release in a meadow, such as the soil nitrogen released at the time of ploughing of old pasture[15], nitrogen derived from applied barnyard manure, and nitrogen fixed by legumes. The amount of released nitrogen from soil

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or legumes varies considerately with the age of the meadows[15] or botanical composition[2,13].

The purpose of this paper was to clarify the relationship between the changes in grass yield with years after establishment and the uptake of fertilizer nitrogen applied to the meadow in terms of decomposition of organic residues on the surface layer which accumulate year by year after establishment.

In this paper the main results obtained in a previous report[10] are summarized. The studies were carried out at the Hokkaido Prefectural Tenpoku Agricultural Experiment Station in the northern part of Hokkaido, Japan.

Changes in grass yield and accumulation of organic residues with year after establishment

1) *Changes in grass yield with year after establishment*

Experimental meadows (orchardgrass-dominant meadow) were prepared by renovation of old meadows every year from 1977 to 1988, in order to compare once grass growth in the meadows with different ages to avoid the influence of climatic variations, such as precipitation, etc. in the northern part of Hokkaido[5,9]. Dry matter yield per year did not decrease with the increase of the meadow age under optimum fertilizer nitrogen application (N 180 kg $ha^{-1}y^{-1}$). However, when the application of fertilizer nitrogen was insufficient (N 120 kg $ha^{-1}y^{-1}$), grass yield of more than 9 years old meadows decreased. The marked decrease in the grass yield resulted from the low yield of the first cutting in these old meadows. The relative yield of 7 and 8 years old meadows and that of a meadow more than 9 years old were 95 and 82%, of that of a 3 years old meadow, respectively. On the other hand, the yield of the second and third cuttings of these old meadows was higher than that of the 3 years old meadow (Table 1). Therefore, the yield increment of the first cutting by unit amount of fertilizer nitrogen applied increased along with the increase of the meadow age.

2) *Uptake of applied fertilizer nitrogen in meadows with different ages*

In meadows more than 9 years old, both the uptake of applied fertilizer nitrogen and release of soil nitrogen at the first cutting stage were lower than those of 2 and 3 years old meadows (Table 2). It was also recognized that the uptake of applied fertilizer nitrogen in old meadows was lower than that of younger meadows at the second and third cutting stages. However, the release of soil nitrogen in old meadows was larger than that in younger meadows due to the increase of the soil temperature at the second or third cutting stages. As a result, grass yields of old meadows in the second and third cuttings were nearly equal to or higher than those of young meadows. Grass growth in autumn after the third cutting in old meadows was less active than that of younger meadows since the amount of soil nitrogen released in older meadows was smaller than that in younger meadows at a low soil temperature. Thus, the difference in grass growth in older or younger meadows in autumn reflected the extent of the first cutting yield in the following spring.

Table 1. Changes in dry matter yield with years after establishment (1983-1990)

($Mg\ ha^{-1}$)[1)]

N application (N kg ha^{-1})		Meadow age (years old)				
		2 (n = 8)[2)]	3 and 4 (n = 15)	5 and 6 (n = 11)	7 and 8 (n = 9)	More than 9 (n = 9)
120	Total yield	7.64 ± 0.43^a	6.38 ± 0.34^b	6.34 ± 0.42^b	6.30 ± 0.29^b	6.19 ± 0.42^b
	1 cutting	2.94 ± 0.43^a	2.32 ± 0.30^b	2.30 ± 0.31^b	2.20 ± 0.17^b	1.91 ± 0.34^c
	2 cutting	2.60 ± 0.35^a	2.22 ± 0.22^b	2.18 ± 0.19^b	2.27 ± 0.26^b	2.27 ± 0.25^b
	3 cutting	2.10 ± 0.52	1.84 ± 0.43	1.86 ± 0.51	1.83 ± 0.46	1.99 ± 0.49
180	Total yield	9.60 ± 0.70^a	8.33 ± 0.50^b	8.11 ± 0.39^b	8.39 ± 0.35^b	8.32 ± 0.52^b
	1 cutting	3.53 ± 0.52^a	3.02 ± 0.41^b	2.97 ± 0.40^b	2.94 ± 0.28^b	2.81 ± 0.35^b
	2 cutting	3.33 ± 0.27^a	2.86 ± 0.18^b	2.77 ± 0.24^b	2.98 ± 0.14^b	2.98 ± 0.26^b
	3 cutting	2.74 ± 0.54	2.44 ± 0.49	2.37 ± 0.59	2.47 ± 0.39	2.53 ± 0.54

1): 1 Mg ha^{-1} is the same as 1 t ha^{-1}.
2): Values in parentheses indicate the number of meadows studied (1983-1990).
Superscript letters (a, b, c) show significant difference ($P < 0.05$, t-test).

Table 2. Nitrogen uptake from fertilizer N and soil N in meadows with different ages (1985)

Meadow age (years old)	1st cutting stage (9.8)[1)		2nd cutting stage (15.5)		3rd cutting stage (18.7)		Growth stage in autumn (8.5)	FN recovery	Total amount of SN	1st cutting yield[4)
	FN[2)	SN[3)	FN	SN	FN	SN	SN	(%)	taken up	(DM, Mg ha^{-1})
2	20.7	19.9	18.6	21.8	20.2	22.8	8.1	49	72.6	2.83
3	16.7	14.9	17.5	17.9	19.7	24.1	7.9	45	64.8	2.63
4	17.7	14.0	16.4	17.3	15.8	25.0	9.1	42	65.4	2.90
5	17.1	19.0	16.3	25.5	15.8	32.8	6.9	41	84.2	2.58
9<	12.9	9.6	16.6	23.8	14.9	30.8	6.0	37	70.2	2.24

1): Values in parentheses indicate average temperature (°C) during each growth stage.
2): FN: Fertilizer nitrogen marked with $(^{15}NH_4)_2SO_4$ and applied at 40 kg N ha^{-1} at each cutting stage (3 times a year, kg N ha^{-1}).
3): SN: Amount of nitrogen taken up from soil at each cutting stage (kg N ha^{-1}).
4): Yield of first cutting in the following spring.

3) Characteristics of soil organic nitrogen release from the surface layer in meadows with different ages

It was estimated that the annual production of dead herbage and roots amounted to 4,000 kg ha^{-1} and the amount of nitrogen retained in them ranged from 40 to 50 kg $ha^{-1}y^{-1}$. The rate of accumulation on the surface layer (0-5 cm) amounted to 1,000 kg ha^{-1} of organic residues and 20 kg ha^{-1} of nitrogen per year. Then, in a 10 years old meadow, the amount of accumulated organic residues and nitrogen was about 10 Mg ha^{-1} and 200 kg ha^{-1}, respectively (Fig. 1a). C/N ratios of residues from dead stubbles on the surface and residues larger than 2 mm in diameter on the surface layer (0-5 cm) were larger in the older meadows than in the younger ones (Fig. 1b).

Organic nitrogen mineralization pattern of the soil surface layer soil fitted to a two-simple-type model developed by Sugihara et al.[14]. The model consists of two components; rapid release soil organic nitrogen and slow release one. Nitrogen mineralization potential (N_01) of the rapid release part of organic nitrogen decreased, while that of N_02 of the slow release part increased with the increase of the meadow age. Apparent activation energy values (Ea1, Ea2) of both components increased with the increase of the meadow age (Table 3). Moreover, the immobilization of fertilizer nitrogen increased in an older meadow compared with a younger one due to the accumulation of organic residues with a large C/N ratio along with the increase of the age of the meadow. Also, the release of immobilized fertilizer nitrogen decreased in the surface layer of soil in

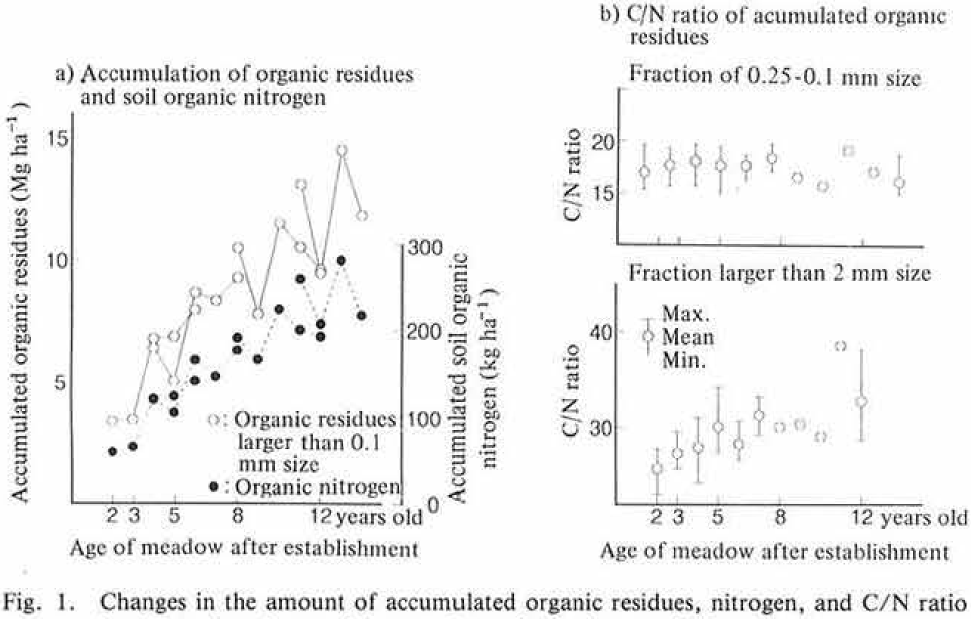

Fig. 1. Changes in the amount of accumulated organic residues, nitrogen, and C/N ratio in the surface layer with age of meadow after establishment

Table 3. Nitrogen mineralization parameters[1)] of surface layer from soils of meadows with different ages (incubation experiment using air-dried soils)

Kind of meadows (years old)	Rapid release part of organic nitrogen (N1)			Slow release part of organic nitrogen (N2)		
	$N_0$1 (mg kg^{-1})	K1 (20°C) (10^{-3}d^{-1})	Ea1 (J mol^{-1})	$N_0$2 (mg kg^{-1})	K2 (20°C) (10^{-3}d^{-1})	Ea2 (J mol^{-1})
3	59 ± 4	1.2 ± 0.2	3,200 ± 359	284 ± 15	0.03 ± 0.003	3,420 ± 100
5	53 ± 6	0.9 ± 0.2	3,820 ± 620	446 ± 39	0.02 ± 0.004	3,730 ± 120
10	37 ± 11	2.5 ± 1.6	5,660 ± 2,270	385 ± 12	0.05 ± 0.004	4,060 ± 120

1): Decompositionn of organic nitrogen was derived from the equation:

$$N = N_0 1\ [1-\exp(-K1 \cdot T)] + N_0 2\ [1-\exp(-K2 \cdot T)].$$

N_0: Nitrogen mineralization potential, K: Constant of mineralization at 20°C, Ea: Apparent activation energy.

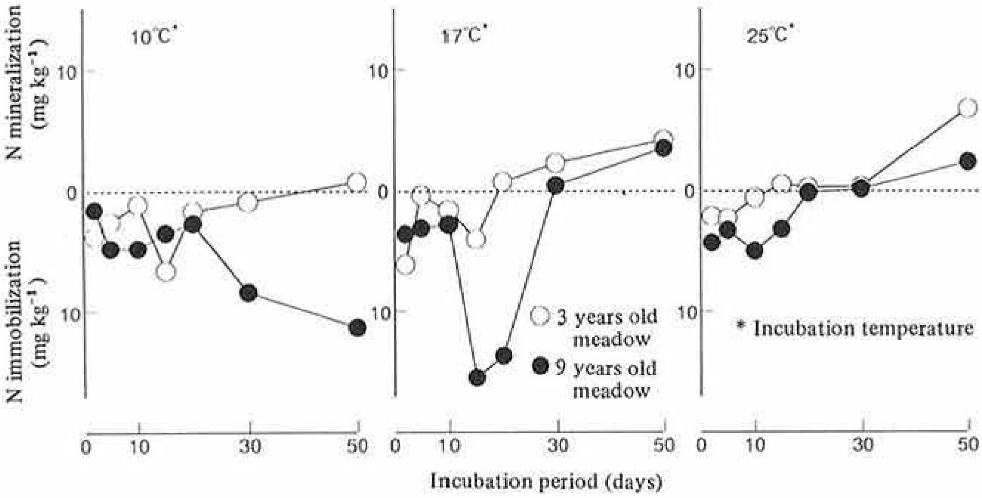

Fig. 2. Effect of incubation temperature on immobilization and re-mineralization of fertilizer nitrogen in the surface layer of soil (0–5 cm depth) in meadows with different ages

old meadows, especially at a low soil temperature (Fig.2).

4) Changes in soil and applied fertilizer nitrogen balance with year after meadow establishment

Total nitrogen content in the surface layer of soil (0 to 2 cm thick) remarkably increased because the accumulation of dead materials is concentrated on the surface layer while that in the 5 to 15 cm layer decreased until the 6th to 8th year after establishment. Therefore, the soil nitrogen status was almost constant in the 0 to 15 cm layer. The rate of nitrogen uptake by grass in the period from 2 to 12 years amounted to 90 to 113% of applied fertilizer nitrogen. The amount of nitrogen uptake in 2 to 4 years old meadows was larger than that of applied fertilizer nitrogen. However, in 6 to 8 years old meadows, a part of applied fertilizer nitrogen was immobilized in the soil. Then, the soil nitrogen status during 10 years apparently remained at the same level as that at the time of establishment. Due to the balance between the amount of fertilizer nitrogen, i.e. uptake of nitrogen by grass and soil nitrogen, the loss of applied fertilizer nitrogen was estimated to be very low, ranging from about 6% in an N 120 kg ha^{-1} plot to 9% in an N 180 kg ha^{-1} plot (Table 4).

The amount of easily decomposable organic nitrogen of the surface layer (0–5 cm) measured by the fresh soil incubation method at 30°C, in a 30-day period under field water capacity conditions using undestructed surface layer sample increased while that in the 5 to 15 cm layer soil decreased with the age of the meadow as in the case of the total soil nitrogen content. However, the sum of the amount of easily decomposable nitrogen of the 0 to 15 cm thick layer was almost constant with the years, except for the period of 1 and 2 years after establishment (Fig. 3).

Table 4. Nitrogen balance in meadows with different ages

	Plot of FN 120 kg $ha^{-1}y^{-1}$						Plot of FN 180 kg $ha^{-1}y^{-1}$		
Meadow age (years old)	2	4	6	8	10	12	2	6	12
Total amount of FN applied[1]	120	360	600	840	1,080	1,320	180	900	1,980
Total amount of N taken up[2]	135	369	600	821	1,043	1,259	186	832	1,788
Amount of retained N[3]	6	12	16	19	21	23	8	17	25
Sum of N amount taken up and retained[4]	141	381	616	840	1,064	1,282	194	849	1,813
Apparent FN recovery[5]	113	103	100	98	97	95	103	92	90
N taken up from SN[6]	21	21	16	0	− 14	− 38	14	− 51	− 167
Fluctuations in SN[7]	− 37	− 9	− 55	− 35	+ 34	− 3	− 45	− 17	+ 25
Balance of SN[8]	− 16	+ 12	− 39	− 35	+ 17	− 41	− 31	− 68	− 143

1): Total amount of fertilizer nitrogen applied to meadows from 2 to 12 years after establishment (kg ha^{-1}).
2): Total amount of nitrogen taken up by grass in meadows from 2 to 12 years after establishment (kg ha^{-1}).
3): Amount of nitrogen retained in stubbles and roots of grass (kg ha^{-1}).
4): Sum of nitrogen amount taken up and retained nitrogen by or in grass [2) + 3): kg ha^{-1}].
5): Proportion of total amount of nitrogen taken up by grass to total amount of applied fertilizer nitrogen [2)/1) × 100: (%)].
6): Difference in the sum of nitrogen amount taken up and retained by or in grass and total amount of fertilizer nitrogen applied [4) − 1): kg ha^{-1}].
7): Fluctuations in soil nitrogen amount in 0 to 15 cm layer, indicating the difference between the amount of soil nitrogen at the time of resowing and that of meadows with respective ages (kg ha^{-1}).
8): Balance of soil nitrogen indicating the difference between the amount of soil nitrogen taken up by grass and the fluctuations in the soil nitrogen amount [6) − 7): kg ha^{-1}].

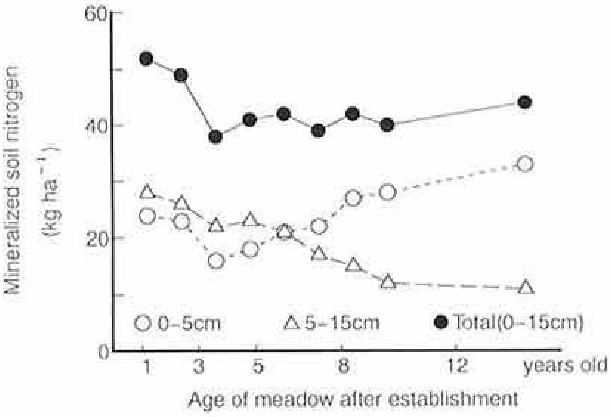

Fig. 3. Changes in the amount of mineralized soil nitrogen with the age of the meadow after establishment

Limiting factors of grass yield and decomposition of organic residues

Decomposition rate of returned organic residues was affected by the cumulative precipitation during the grass-growing period, i.e. from late April to mid-September (Fig. 4a). The amount of accumulated nitrogen decreased in years with high precipitation as compared with the previous year (Fig. 4b). Also, other experiments revealed that the amount of accumulated organic residues and nitrogen of the meadow decreased by irrigation.

The sum of the yield of the second and third cuttings increased with the increase in cumulative precipitation in July to August, in particular in old meadows (Fig. 5a). The relationship between the relative yield of old meadows as compared with that of 3 and 4 years old meadows and the amount of precipitation enabled to obtain three levels of precipitation (Fig. 5b). The relative yield of old meadows was higher than that of younger meadows (3 and 4 years old) when the cumulative precipitation in these periods exceeded 250 mm. However, when the precipitation was low (around 150 mm), the relative yield in old meadows was lower than in younger meadows and there was no difference in the relative yield between old meadows and younger ones for a precipitation around 70 mm.

Also cumulative precipitation in the grass-growing period from late April to mid-September of the previous year was less than 400 mm, and the yield of the first cutting was lower than that when the precipitation exceeded 400 mm. These tendencies

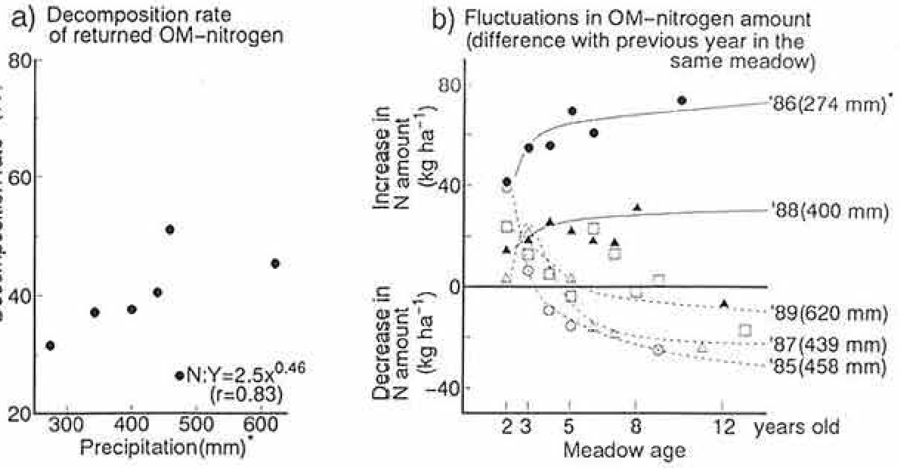

Fig. 4. Effect of amount of precipitation in grass growing period on decomposition rate and fluctuations in organic matter nitrogen amount
*Amount of precipitation during late April to mid-September.

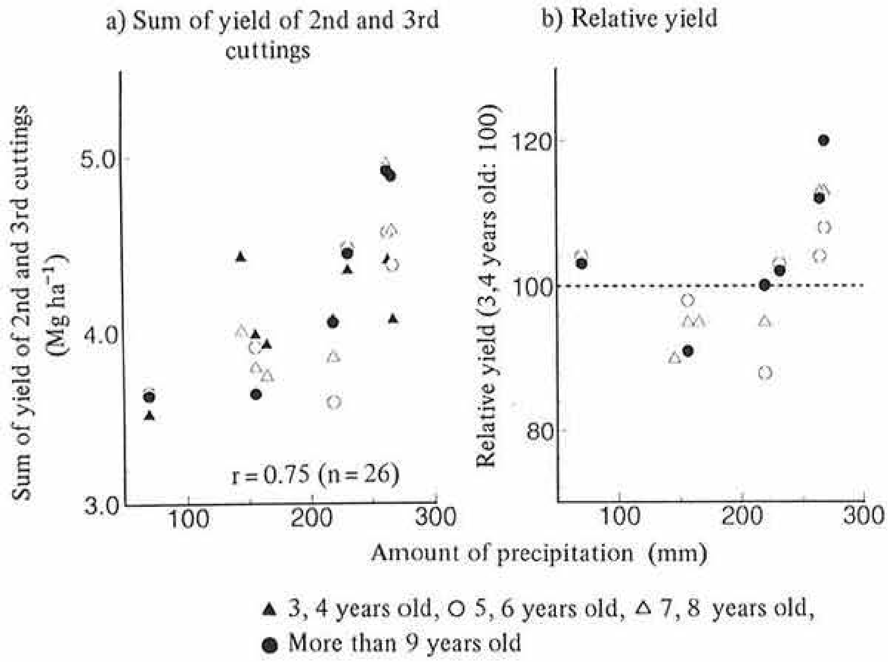

Fig. 5. Sum of yield of second and third cuttings affected by the changes in the amount of precipitation in July and August

were clearly evident in meadows more than 9 years old (Table 5).

These results were attributed to the amount of nitrogen released from soil in old meadows, in which the top layer that supplies mineralized nitrogen became thinner (Fig. 3) since this layer was affected by the level of precipitation as follows: (1) Since the amount of precipitation in July to August was very small (nearly 70 mm, equivalent to about 1.2 mm per day), grass yield decreased due to water deficiency regardless of meadow age. (2) Low precipitation level around 150 mm (equivalent to about 2.5 mm per day) enabled to cover the requirements of diurnal evapotranspiration of grass, but led to water deficiency of the top layer soil due to the predominant water consumption of grass. Grass yield of old meadows was lower than that of younger meadows since soil nitrogen release decreased due to the delay in the decomposition of accumulated organic residues. (3) Precipitation level exceeding 250 mm (equivalent

Table 5. Effect of precipitation in previous summer on grass growth in following spring (1984 – 1990)

Previous summer[1] / Meadow age (years old)	Plot of FN 120 kg $ha^{-1}y^{-1}$					Plot of FN 180 kg $ha^{-1}y^{-1}$				
	2	3, 4[2]	5, 6	7, 8	9<	2	3, 4[2]	5, 6	7, 8	9<
Normal (wet) summer (A)	117	(2.47)	98	93	86	106	(3.23)	101	95	94
Dry summer (B)	136	(2.20)	97	95	75	128	(2.84)	93	98	90
B/A × 100 (%)	103	89	88	91	77	106	88	81	91	84

1): Normal (wet) summer: Precipitation >400 mm/grass growing period (late April to mid-September).
Dry summer: Precipitation <400 mm/grass growing period (late April to mid-September).

2): Data of 3 and 4 years old meadows represent the real dry matter yield (Mg ha^{-1}), and the others indicate the relative yield as compared with the yield of 3 and 4 years old meadows.

to more than 4.2 mm per day) enabled to cover the diurnal evapotranspiration requirements of grass and also to maintain wet conditions in the top layer of soil. Grass yield of old meadows was higher than that of younger meadows since the soil nitrogen release increased due to the large decomposition of accumulated organic residues.

Conclusion

It was observed that the amount of accumulated organic residues and nitrogen retained in them increased in the surface layer with the time after establishment, and that the C/N ratio increased along with the meadow age. These characteristics of accumulated organic residues and changes in the mineralization of soil nitrogen and immobilization of applied fertilizer nitrogen affected the uptake of fertilizer nitrogen by grass.

Grass yield of older meadows was lower than that of younger meadows due to the release of immobilized fertilizer nitrogen and the amount of soil nitrogen decreased at the first cutting stage when the soil temperature was low. However, the release of soil nitrogen in older meadows was larger than that in younger meadows due to the increase of the soil temperature at the second or third cutting stage. As a result, grass yields in older meadows were nearly equal to or higher than those of younger meadows at the second and third cutting stages. These relationships are schematically represented in Fig. 6.

In addition, the sum of the yield of the second and third cuttings was influenced by cumulative precipitation during the period July to August. The sum of grass yield in old meadows was lower than that of younger meadows when cumulative precipitation was low (around 150 mm), while the sum of grass yield in old meadows was higher than that of younger meadows when cumulative precipitation exceeded 250 mm. These results were attributed to the amount of nitrogen released from soil in old meadows, in which the top layer that supplies mineralized nitrogen became thinner since this layer was affected by the level of precipitation.

On the basis of these results, it was considered that nitrogen should be applied in autumn or that

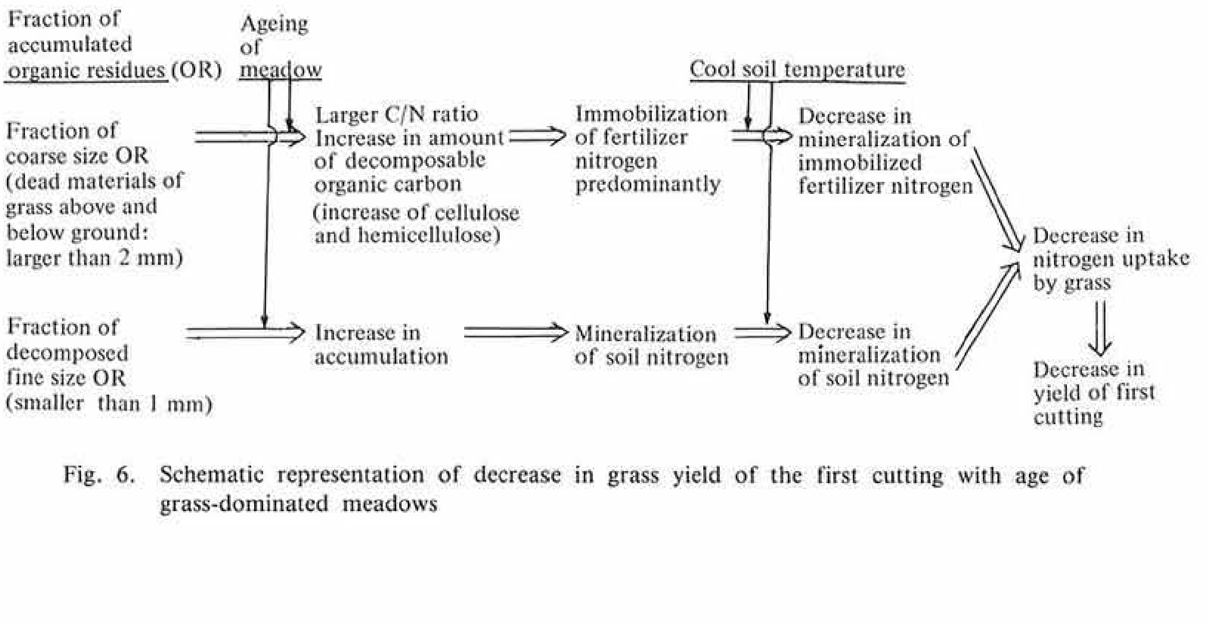

Fig. 6. Schematic representation of decrease in grass yield of the first cutting with age of grass-dominated meadows

the amount of nitrogen fertilizer applied should increase in the early spring of the following year in old meadows. The increment of fertilizer nitrogen in the following spring was about 10 kg N ha^{-1} when the amount of precipitation exceeded 400 mm, and about 20 kg N ha^{-1} when the amount of precipitation was less than 400 mm in the grass-growing period from late April to mid-September in the northern part of Hokkaido. Furthermore, it is necessary to determine the amount of effective fertilizer nitrogen application to sustain grass yield for many years after meadow establishment. To achieve this objective, the amount of nitrogen released at the time of ploughing of old pasture, from applied barnyard manure, as well as from legumes introduced into the meadow should be determined, because the amount of nitrogen released from soil or legumes varies with the age of the meadows or their botanical composition.

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