携帯用スペクトロメータを用いたイタリアンライグラス草地の生育条件の把握

誌名	日本草地学会誌
ISSN	04475933
著者名	板野,志郎 秋山,侃 渡辺,也恭 大久保,忠旦 橋本,靖
発行元	日本草地学会
巻/号	47巻3号
巻号補足	
掲載ページ	p. 237-244
発行年月	2001年8月

Grassland Science 47 (3) : 237–244 (2001)

The Determination of Growth Condition in Italian Ryegrass (*Lolium multiflorum* Lam.) Meadows with a Hand-held Spectrometer

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(Received : August 8, 2000/Accepted : March 5, 2001)

Synopsis

Itano, S., T. Akiyama, N. Watanabe, T. Okubo and Y. Hashimoto (2001) : The determination of growth condition in Italian ryegrass (*Lolium multiflorum* Lam.) meadows with a hand-held spectrometer. *Grassland Science* 47, 237–244.

Experiments to determine grassland features using spectral characteristics were performed. Spectral reflectance was measured, using a hand-held spectrometer, at 102–151 random points in five Italian ryegrass (*Lolium multiflorum* Lam.) meadows under different vegetation conditions. The measurements were used for three applications : 1) to visualize the relationship between red and near infrared spectral characteristics, 2) to determine the spatial pattern of aboveground biomass and apply it to gamma distribution, and 3) to determine the spatial pattern of plant coverage. The red-near infrared spectral reflectance relationship that was derived was a brief and clear index for the degree of dense or sparse coverage or the area of bare soil in grassland. Analysis of the biomass and coverage histograms determined different patterns for different plant growth or grassland conditions. Biomass distribution could be determined more accurately, both qualitatively and objectively, by applying the gamma distribution. These results suggest that several kinds of grassland features could be determined in a short period of time using spectral data measured with a hand-held spectrometer.

Key words : Biomass distribution, Italian ryegrass, Plant coverage, Spatial pattern, Spectral reflectance, Vegetation diagnosis.

Introduction

The introduction of mechanical sensors to measure grass vegetation has been required in order to develop objective and immediate management techniques for grasslands. A hand-held spectrometer precisely and rapidly quantifies the characteristic spectrum of the object that is being studied. Various vegetative features of grasses, such as plant growth, plant form, and soil conditions, have direct effects on their spectral characteristics, and the spectrum that is specifically expressed under the existing conditions can be measured. Some researchers have reported relationships between the measured spectrum and physical or physiological grass parameters[3,4,10,13]. By understanding the relationships between vegetation and spectral characteristics over entire grasslands, we may be able to effectively diagnose plant growth. Satellite spectral image maps have also been adopted to determine spectral characteristics in whole grasslands. Using spectral data, Akiyama *et al.*[1,2] and Rouse *et al.*[11] diagnosed global area of grassland. However, to diagnose complex grasslands, such as those in Japan, which are intensively managed and have variable grass species, we need to continuously measure many points within a range of one location in a short time. A hand-held spectrometer should therefore prove useful in efficiently analyzing such grasslands. However, little research on vegetation in whole grasslands using hand-held spectrometers has been published.

There are many parameters that can be used to determine grassland conditions, including biomass, coverage, frequency, density, leaf color, and species composition. Studies using each of these parameters have been performed, for example, biomass[18], biomass distribution[14,15], and coverage and frequency[7].

Table 1. Outline of Italian ryegrass meadows after first cutting.

Fields and tests		Outline
Field A : Gley soil, 5,000 m^2		
A1	Measured date & time	May 22, 1998. 10 : 40–11 : 40 JST
	Measured points	151 points
	Illuminance	95,000–97,000 lux
	Growth stages	Pre-heading, dense vegetation, *PH* : 0–55 cm
A2	Measured date & time	May 27, 1998. 11 : 00–12 : 00 JST
	Measured points	143 points
	Illuminance	103,000 lux
	Growth stages	Partial heading (the rate of 20–30%), dense vegetation, *PH* : 0–65 cm
A3	Measured date & time	June 4, 1998. 13 : 00–14 : 20 JST
	Measured points	122 points
	Illuminance	35,500–100,000 lux
	Growth stages	All post-heading, dense vegetation, partially lodging, *PH* : 0–70 cm, *HH* : 0–90 cm
A4	Measured date & time	June 12, 1998. 13 : 00–14 : 10 JST
	Measured points	157 points
	Illuminance	97,000 lux
	Growth stages	All post-heading, dense vegetation, frequently lodging, *PH* : 0–70 cm, *HH* : 0–100 cm
Field B : Ando soils, 5,000 m^2		
B1	Measured date & time	June 11, 1998. 11 : 00–12 : 00 JST
	Measured points	105 points
	Illuminance	85,000–88,000 lux
	Growth stages	All post-heading, rough vegetation, some bare soils, *PH* : 0–60 cm, *HH* : 0–70 cm

PH : Plant height (cm), *HH* : Plant head height (cm).

Practical diagnosis of grassland should be decided only after considering several plant parameters, as grassland management involves the both of productivity and preservation. However, measuring different plant parameters simultaneously in a short period is both tedious and time consuming. The use of spectral characteristics, measured over many wavelength regions simultaneously, may alleviate some of the difficulties. Itano *et al.*[5] determined plant parameters such as aboveground biomass, plant coverage, and plant height by using a hand-held spectrometer.

The purpose of this study is to determine the existing grassland conditions using a hand-held spectrometer. We surveyed meadows of Italian ryegrass (*Lolium multiflorum* Lam.) after the first cut, under five different growth stages or vegetation conditions. We studied the spectral reflectance at many points in the meadows for two reasons : 1) to develop grassland diagnosis techniques using spectral characteristics, and 2) to survey different grassland conditions using these diagnostic techniques.

Materials and Methods

1. Study sites and spectral measurements

Measurements were made after the first cut in Italian ryegrass (*Lolium multiflorum* Lam.) meadows at Gifu University (field A : area=5,000 m^2, 35°27′N, 136°44′E) and at Minokamo Farm, which is affiliated with the university (field B : area=5,000 m^2, 35°26′N, 137°44′E). The outline and sward characteristics of each test are shown in Table 1. The field investigation was conducted from May 22 to June 12, 1998. Field A was a high population density meadow on gley soils, and four investigations : Tests A1-A4 were made as the grass sward grew. Test A1 was in the meadow before heading ; Test A2 was after partially heading ; Test A3 was after heading ; and Test A4 was with lodging after further growth. Field B was a meadow and had poor growth, with many bare patches, on ando soils ; one investigation, Test B1, was made after heading.

Two directional spectral factors (hereafter called spectral reflectance) were measured at 102–151 random points for each test. The measurements were made 1.5 meters above the ground, between 10 : 30 and 14 : 30 JST on clear days when the sun was high in the sky. To measure the spectral reflectance, we used a hand-held spectrometer (Prede Co. Ltd.). The instantaneous field-of-view angle of this device is 20 degrees ; therefore, a circular area 0.53 m in diameter on the ground surface was measured. Please refer to a previous report[5] for details concerning this apparatus and its use.

In addition, to examine the variation of spectral characteristics for areas with vegetation versus

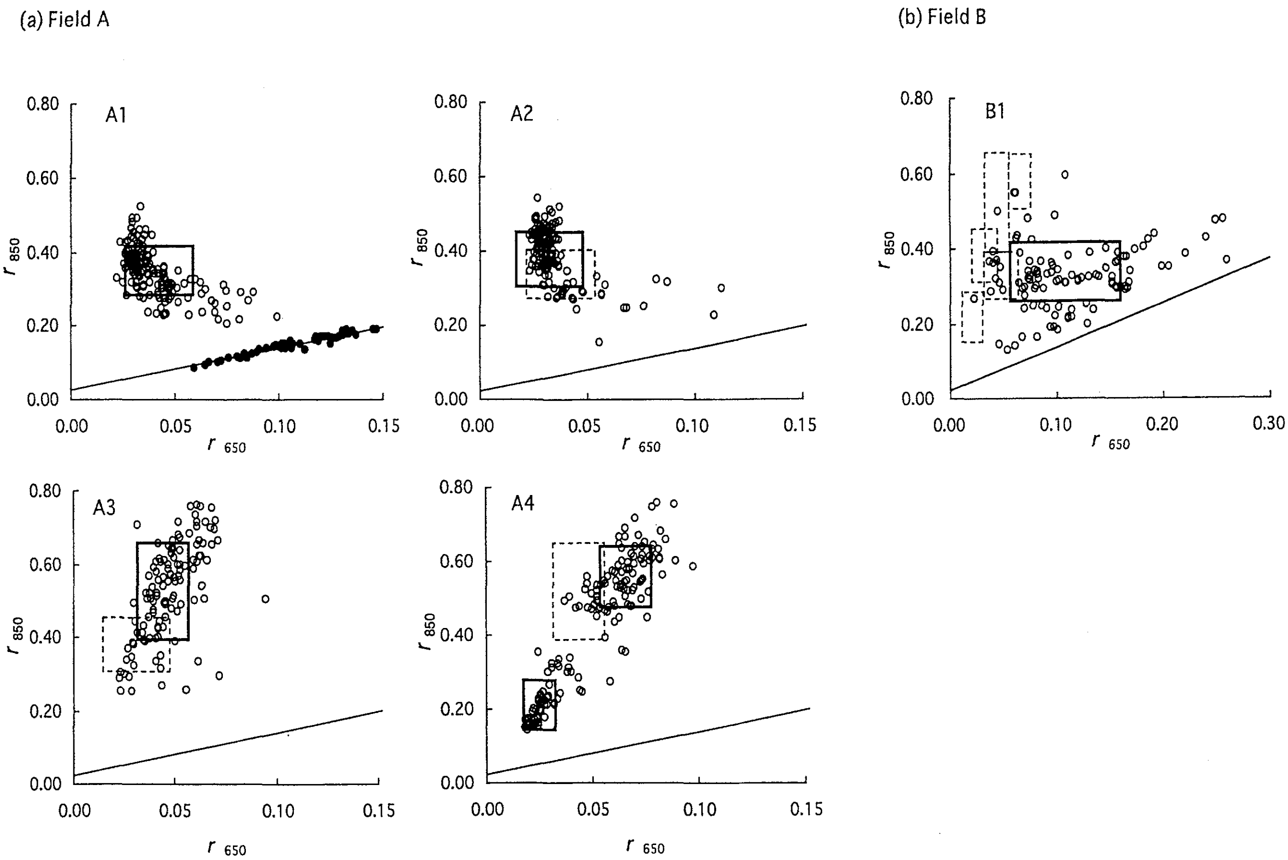

Fig. 1. The distribution of spectral reflectance between visible red range 650 nm and near infrared range 850 nm in each test. Solid circles and straight lines shows soil spectrum under cultivated field near field A, in May 27 and June 4, 1998. The means±SD of r_{850} and r_{650} for each test are encircled with solid rectangle frames. In Test A4, the frames are added to separated two groups, respectively. Broken rectangle frames in field A and B shows the means±SD of ex-growth stage, and their values of all tests in field A, respectively.

those with no vegetation, we measured spectral reflectance on bare land. The measurements were conducted in a bare field near field A that was plowed on May 27 and June 12, 1998 ; the spectral reflectance of the soil was measured randomly at 58 points.

2. Data analysis

We used spectral reflectance at 650 nm and 850 nm measured, which is often adopted as vegetation index, in order to attempt to apply three techniques : 1) to visualize a relationship between red and near infrared spectral characteristics ; 2) to determine the distribution pattern for aboveground biomass for each test and apply it to SHIYOMI's gamma distribution index ; and 3) to determine the distribution pattern of plant coverage for each test.

To calculate the aboveground biomass (*AB*, g DM/m²) and the plant coverage (*PC, %*) from spectral characteristics, we adopted the following equations from ITANO *et al.*[5] :

$$AB\ (\mathrm{g\,DM/m^2})=1195.06KVI-76.90 \qquad r^2=0.95\ (1)$$

$$KVI=r_{850}-1.035\,r_{650}-0.0374,$$

$$PC\ (\%)=152.00NDVI-37.34 \qquad r^2=0.97\ (2)$$

$$NDVI=(r_{850}-r_{650})/(r_{850}+r_{650}).$$

The *r*-numbers represent the spectral reflectance for each wavelength region. *KVI* and *NDVI*, which are calculated from the spectral reflectance, are called the vegetation index. The coefficients in the *KVI* equation were estimated according to SAITO and FUKUHARA's method[12] from the spectral reflectance of the soil of plowed fields near field A. These equations were made by using the aboveground biomass, plant coverage, and spectral reflectance data measured in fields A and B within the same experimental period[5].

SHIYOMI's model, which was adopted for the frequency of aboveground biomass, *AB*, can be expressed as follows :

$$f(AB)\ dAB=\frac{AB^{P-1}P^P}{\Gamma\ (P)\mu^P}e^{-PAB/\mu}\,dAB,$$

where μ and P denote the average biomass and a parameter concerning a shape of distribution, respectively.

Results

1. Relationship between red and near infrared spectral characteristics

Figure 1 shows the relationship of spectral refle-

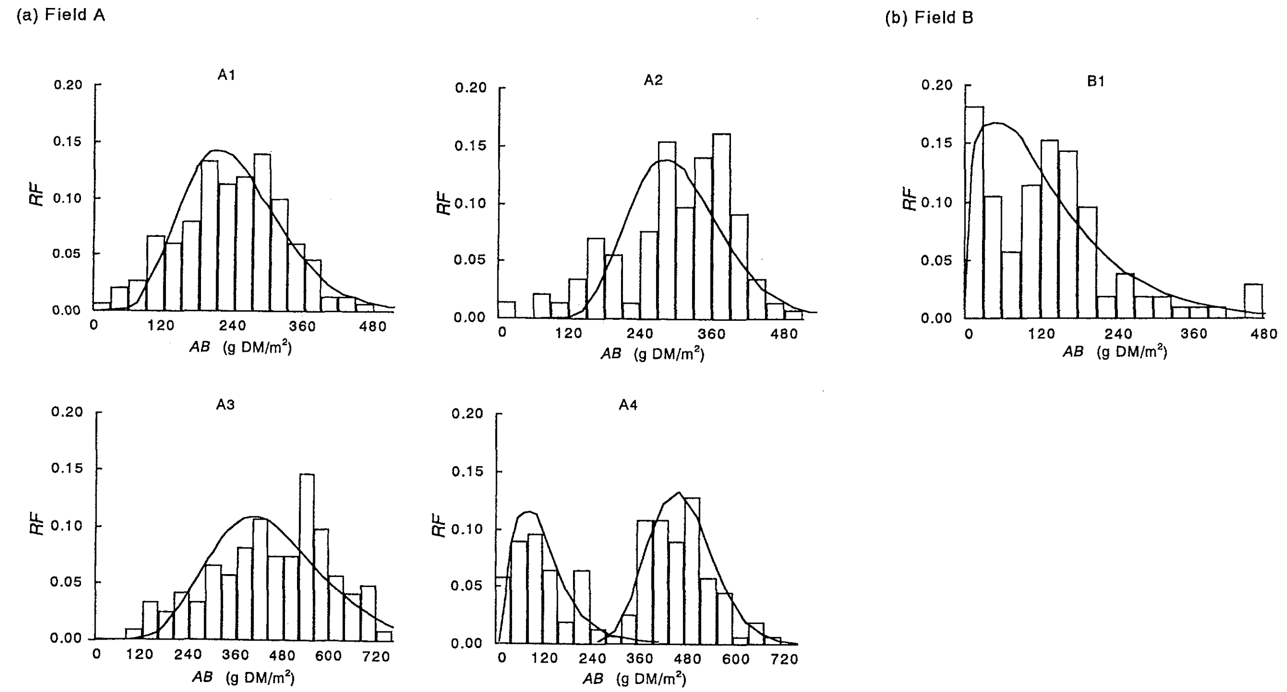

Fig. 2. The histogram of aboveground dry biomass : AB (g DM/m^2) calculated from spectrum in each test. RF : relative frequency. Solid lines show the transformation of biomass histogram into γ distribution of functions. The γ distribution of test A4 was shown by dividing biomass data into two groups at 280 g DM/m^2.

ctance in the near infrared band of 850 nm, r_{850}, with the red band of 650 nm, r_{650}, for each test. This relationship will hereafter be called "rR-IR". Straight lines in the figure, called the soil lines, were determined by analyzing the linear regression of rR-IR measured in the plowed fields near field A. The points of rR-IR for the plowed soil accurately fit the soil line ; the coefficient of determination was 0.96 ($P < 0.0001$). Assuming fields A and B did not differ much in the rR-IR for the soils, we applied the same soil line to both. As shown in Fig. 1, points of rR-IR for all the tests were plotted over the soil line ; their distribution pattern depended on the growth stage or the vegetation conditions of each test.

Many rR-IR for Test A1, with the youngest sward before heading, were concentrated in the 0.03–0.05 range for r_{650} and in the 0.2–0.5 range for r_{850} (63.6 %), but more points were plotted above $r_{650}=0.05$, near the soil line, than for the other growth stages in Tests A2-A4 (A1 : 17.2 %, A2-A4 : 2.5–8.4 %). In Test A2, in which the plants were growing more, the mean±SD of r_{850} in the range $r_{650} \leq 0.05$ was 0.40±0.06, higher than the 0.36±0.06 for Test A1. In Test A3, which had dense vegetation after heading, few points were in the range of $r_{850} \leq 0.30$ or $r_{650} \geq 0.05$; the mean±SD of r_{850} was 0.53±0.13, higher values than in Tests A1 and A2. This implies that the spectral reflectance in the near infrared region increased with the growth of the plant sward.

In Test A4, which had more heading plants and many lodging points, there were few points in the ranges $r_{850} \leq 0.30$ and $r_{650} \geq 0.05$, and the rR-IR values separated into two groups near $r_{850}=0.40$. As described later, this implies that the rR-IR can determine whether a plant is standing or lodging in the meadows. Here the rR-IR group on the lower left in the ranges $r_{850} < 0.40$ showed lodging points ; the means±SD of r_{850} and r_{650} were 0.22±0.06 and 0.03±0.01, respectively. The values of r_{850} and r_{650} in the rR-IR group of standing points, on the upper right, were 0.56±0.07 and 0.07±0.01, respectively.

In Test B1, of rough vegetation after heading with many bare soil patches, the values of spectral reflectance in the red band, r_{650}, were in a wider range, 0 to 0.3, than those from each test in field A. The mean±SD of spectral reflectance in the near infrared band, r_{850}, was 0.33±0.09, less than in field A, and many points were distributed near the soil line.

2. The distribution pattern of aboveground biomass

Figure 2 shows the histogram of aboveground biomass in each test, as determined by equation (1). The representative values of biomass distribution estimated using the equation in each test are also shown in Table 2. As shown in Fig. 2 and Table 2, the biomass distributions of Tests A1 to A3 were similar to normal distributions, and their means increased with growth (234.93, 298.52, 454.00 g DM/m^2,

Table 2. Representative values for aboveground biomass distribution calculated from spectra.

	Field A						Field B
	A1	A2	A3	A4			B1
				Lodging	Standing	Total	
Measurement number	151	143	122	63	94	157	105
Mean (g DM/m^2)	234.93	298.52	454.00	115.31	466.00	325.28	133.60
Standard deviation (g DM/m^2)	89.07	94.63	148.44	67.57	80.08	187.67	105.95
Coefficients of variance	0.38	0.32	0.33	0.59	0.17	0.58	0.79
Parameter P of γ distribution	6.96	9.95	9.35	2.91	33.87	3.00	1.59
Maximum (g DM/m^2)	460.66	492.49	757.55	275.79	681.99	681.99	456.97
Minimum (g DM/m^2)	22.79	0.00	116.44	25.01	316.33	25.01	0.00

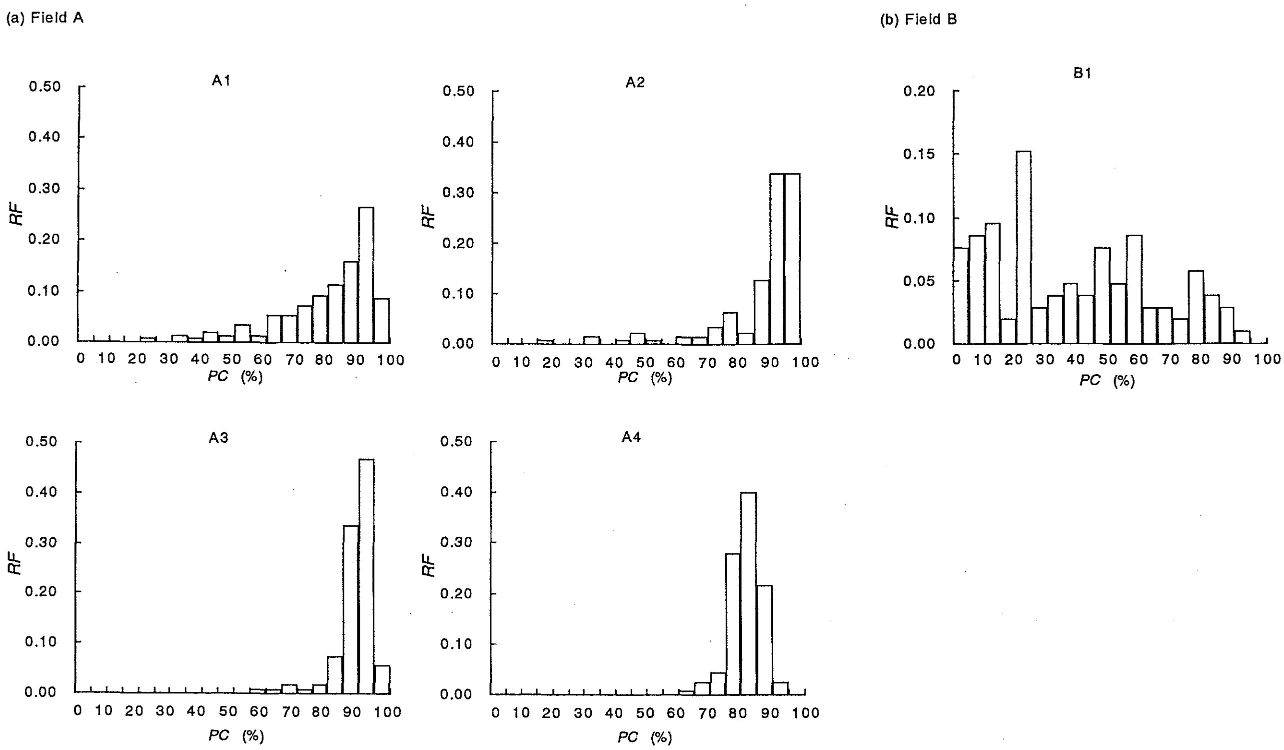

Fig. 3. The histogram of plant coverage calculated from spectrum in each test. *PC* : plant coverage (%) ; *RF* : relative frequency.

respectively). The biomass in Test A3 was widely distributed and divergent. On the other hand, the biomass distribution in Test A4 had peaks for the lodging and standing areas. For the standing areas, the biomass was 466.00±80.08 g DM/m^2 (mean±SD) and showed normality (χ^2=16.01, p>0.05), while the biomass for the lodging areas was 115.31±67.57 g DM/m^2, and didn't show normality (χ^2=38.6, p<0.0001). The biomass in Test B1, with many bare soil patches, did not show normality (χ^2=51.87, p<0.0001).

Aboveground biomass often causes non-normalized distribution. SHIYOMI[14,15] proposed a gamma distribution for such different biomass distributions. The parameter P in this distribution explains the topological heterogeneity of biomass in grassland. If P=1, the distribution pattern is random, if P>1 and has more values, the pattern is more homogeneous. The gamma distribution was applied to the biomass data estimated from the spectra from each test, and was added to each biomass histogram in Fig. 2. The patterns of gamma distribution in each test agreed with the characteristics of the biomass histograms to a considerable extent. As is also shown in Table 2, parameter P increased with plant growth to 9.95 in Test A2 from 6.96 in Test A1. Furthermore, the standing areas in Test A4, in which the plants were growing, showed higher homogeneity with P=33.87.

In Test A3, which included some lodging areas,

Table 3. Representative values for the distribution of plant coverage calculated from spectra.

	Field A						Field B
	A1	A2	A3	A4			B1
				Lodging	Standing	Total	
Measurement number	151	143	122	63	94	157	105
Mean (%)	80.32	88.06	89.08	79.62	82.72	81.47	38.11
Standard deviation (%)	15.43	14.07	6.50	5.77	4.31	5.17	25.73
Coefficients of variance	0.19	0.16	0.07	0.07	0.05	0.06	0.68
Maximum (%)	98.65	100.00	100.00	94.78	93.18	94.78	90.64
Minimum (%)	21.21	16.01	55.05	61.04	70.15	61.04	0.00

parameter P was 9.35 and did not differ from the values in Test A2. The lodging areas of Test A4 showed the most random spatial pattern of all the tests in field A, with a value of $P=2.91$. Test B1, of poor vegetation with many bare soil patches, had a low value of $P=1.59$ and the biomass distribution was the most random pattern seen in this study.

3. The distribution pattern of plant coverage

The histograms and representative values of plant coverage determined for each test by equation (2) are shown in Fig. 3 and Table 3, respectively. The respective plant coverage of lodging and standing areas shown in Table 3 was calculated by using data below or above 280 g DM/m^2 of aboveground biomass, estimated from Fig. 2, respectively.

As shown in Fig. 3 and Table 3, plant coverage increased with plant growth from Tests A1 through A3 ; the mean values were 80.32, 88.06, 89.08%, respectively. Points with less than 60% coverage also had decreasing growth from Tests A1 to A4. The increase of coverage with plant growth between Tests A2 and A3 was less than that between Tests A1 and A2. In contrast, the coverage of standing areas in Test A4 after heading decreased to the mean value of 82.72%. The mean values of coverage of lodging and standing areas in Test A4 were 79.62 and 82.72%, and their coefficients of variation were 0.07 and 0.05, respectively. The difference in the coverage distribution of lodging and standing areas did not indicate a marked difference in biomass distribution. Plant coverage distribution in Test B1 showed more heterogeneity than in all the tests in field A. The coverage varied widely, with a range of 0 to 90.64% ; its coefficient of variation was 0.68, higher than the values for Tests A1-A4 (0.06–0.19).

Discussion

The results of this study support the idea that several kinds of grassland features can be determined using measured spectral reflectance data. We adopted three methods : 1) the determination of a relationship between red and near infrared spectral reflectance for plant condition in grassland ; 2) the analysis of histograms of aboveground biomass and plant coverage ; and 3) the application of biomass pattern to the gamma distribution index. These methods were applied to five meadows with different growth stages or vegetation conditions, and were found to be suitable for determining different grassland features.

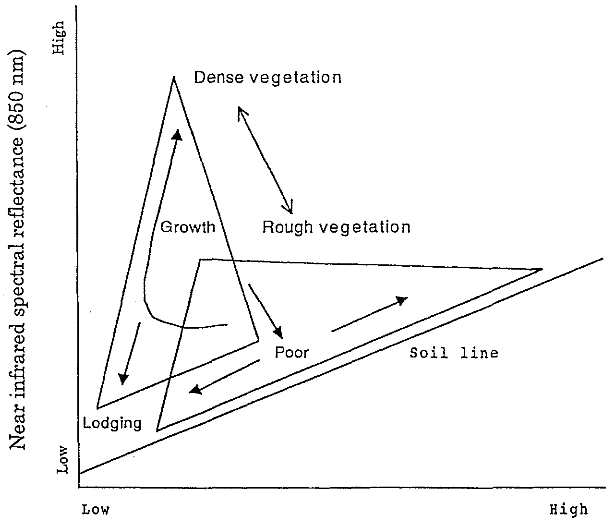

Fig. 4. A schematic diagram of red-near infrared spectral reflectance in grassland. The direction of arrows, and the position or shape of triangles, depend on the degree of growth and vegetation features in grassland.

1. The relationship between red and near infrared spectra

As shown in Fig. 4, the derived red-near infrared spectral reflectance (rR-IR) may be a simple and clear index by which to determine plant growth states, and the degree of coverage or the area of bare soil in grasslands. In this study, the rR-IR points for all the tests were located over the soil line. As the plants grew, spectral reflectance in the near infrared region increased while reflectance in the red region decreased. This was probably because absorption of solar rays in the red region increases as plants grow, due to photosynthetic pigments, and reflection of solar rays in the near infrared region increases due to mesophyllum tissue[17]. This explanation also accounts for the spectral reflectance being higher and more expanded in the red region, while being lower in the near infrared region, near the soil line in rough vegetation with more bare soil patches, such as in field B. The spectral reflectance in the red region of the lodging points in Test A4 was no higher than the rough vegetation points in Test B1. This implies that the biomass in the measured area decreased as a result of lodging, but photosynthetic pigments still sufficiently captured solar rays.

KAUTH and THOMAS[6] first tried to schematically express the rR-IR relationship by considering the spectral characteristics of plants. Using satellite data, they applied this technique to growth changes for crops in a global area. In much the same way, SAITO and FUKUHARA[12] reported growth change in a sugar beet community using a hand-held spectrometer. All of these studies produced useful results, but there are few reports of vegetation diagnosis in grasslands using this technique. This study shows that grassland conditions can be determined, to some extent, using the same method. In addition, as it uses the spectral data directly, this method does not require modification such as the estimation of biomass and coverage from the spectral data measured, and can be readily analyzed. Therefore, it should be effective for abbreviated and direct grassland diagnoses.

2. Distribution of aboveground biomass and plant coverage

Analysis of biomass and coverage histograms is suitable for determining the distribution pattern of grassland vegetation under different conditions. With this technique, however, the regression equations adopted, (1) and (2), must have high accuracy for estimating biomass and coverage. As previously reported[5], the equations precisely quantified the aboveground biomass and coverage in meadows under three different conditions with $r^2=0.95$ and 0.97, respectively. The histograms for biomass and coverage in Figs. 2 and 3, therefore, should accurately represent the actual situation in each meadow. In the same manner as *KVI* adopted in equation (1), perpendicular vegetation index : *PVI*[9] is widely noted as an index from the spectral reflectance of the soil. Since both are based on the same principle, *PVI* should also be used for aboveground biomass.

One result was that the spatial pattern of biomass and coverage was determined for a meadow with many lodging areas after heading (Test A4). In such a meadow, aboveground biomass is distributed bimodally, in lodging and standing areas. The two distributions correspond to the two groups separated in the rR-IR relationship of Test A4 in Fig. 1. MIYAMA *et al.*[8] classified a sugar beet community into two similar distributions, drought-damaged and non-damaged areas. Thus, using the spectral reflectance measured at many points during a fixed period we can determine two or more biomass distributions in grassland.

When comparing simultaneously measured biomass and coverage distributions, we can examine grassland features in detail. In Test A4, the biomass distribution was separated into two groups, while coverage distribution was not separated (Figs. 2 and 3) ; the biomass in standing areas increased with plant growth, but the coverage decreased. This implies that plants lodging in dense vegetation do not always cause a decrease in plant coverage, and the plant morphological changes with heading may decrease plant coverage. It is apparent that the distributions of biomass and coverage in a meadow such as field B, with many bare soil patches, differ from those in a meadow with dense vegetation, such as field A. Examining biomass and coverage distributions could be applied to determining the characteristics of plant forms or the extent of barren land.

3. Utilization of gamma distribution

We tried to apply the estimated biomass histograms to the gamma distribution. Plant biomass does not necessarily show normal distribution and may have distributions ranging from homogeneous to heterogeneous. To express such different distribution patterns as one function, SHIYOMI *et al.*[14,15] proposed the gamma function. He showed that the parameter P in the function could quantitatively represent the topological heterogeneity of biomass in grassland as heterogeneous, random and homogeneous. Therefore, the gamma distribution would be a good index for determining the biomass condition in grassland. However, a large amount of biomass data is required to determine the distribution function. SHIYOMI[16] resolved this problem using a mathematical technique with visual observation, but it is difficult to determine a distribution pattern involving two more peaks, such as was seen in Test A4. Much of the biomass data estimated from spectra could be easily applied to the distribution function, because with a hand-held spectrometer the spectra can be measured objectively in a short time. Using this technique, we can quantify grassland conditions, such as lodging or standing condition, rough or dense vegetation, and the degree of plant growth.

These results suggest that a multi-point investigation of the spectral characteristics of grasslands is suitable for determining plant growth and grassland conditions. In addition, useful diagnosis of grassland can be accomplished by incorporating other sources of information, since some grassland features can rapidly be made using different combinations of spectra, measured by a hand-held spectrometer.

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* : In Japanese with English summary.
** : In Japanese only. Translated title by the present authors.

要　　旨

板野志郎・秋山　侃*・渡辺也恭**・大久保忠旦***・橋本　靖****
(2001)：携帯用スペクトロメータを用いたイタリアンライグラス草地の生育条件の把握. 日草誌 **47**, 237-244. 岐阜大学農学部附属農場(501-1193 岐阜市柳戸)，*岐阜大学流域環境研究センター（501-1193 岐阜市柳戸)，**姫路工業大学自然・環境科学研究所田園生態保全管理研究部門（668-0814 兵庫県豊岡市祥雲寺二ヶ谷)，***那須大学都市経済学部（329-3121 栃木県黒磯市鹿野崎)，****帯広畜産大学畜産環境学科（080-8555 北海道帯広市稲田町西2線11)

草地の状態を分光特性により把握する試験を行った。5つの異なる植生条件下のイタリアンライグラス草地において，携帯用スペクトロメータを用い102点から151点の分光反射率を測定した。測定された分光反射率を次の3つの方法を用いて解析した。1）赤-近赤外域の分光特性の関係の視覚化，2）草量の頻度分布推定とガンマ分布の適用，3）植被率の頻度分布推定。赤-近赤外域の分光反射率の関係は，草地における植生状況の粗密もしくは裸地化の程度を示す簡易指標となった。草量と植被率の頻度分布の解析は，生育段階や草地条件に伴う植生の分布様式の違いを示した。草量分布は，ガンマ分布を適用することで，より正確に客観的かつ量的に捉えることができた。以上の結果は，草地における複数の特徴を，携帯用スペクトロメータで測定された分光データを用いることで，短時間内に把握できることを示した。

キーワード：イタリアンライグラス，空間分布，植生診断，植被率，草量，分光反射.