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Rapid assessments of herbage biomass and quality using field hyperspectral (HS) measurements with 1D-CNN

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Abstract

Assessments of herbage biomass and forage quality using field hyperspectral (HS) sensing provide valuable support to farmers in making precise forage management decisions. The field HS data, which includes measurements of canopy reflectance in the visible and near-infrared wavelength range (400-2350 nm), has been extensively studied in grassland assessment research. Partial least squares (PLS) regression has been widely adopted as a standard calibration method for estimating herbage biomass (BM) and determining forage quality parameters, such as crude protein (CP) and neutral detergent fiber (NDF) concentrations. In this study, a one-dimensional convolutional neural network (1D-CNN) model was developed as a non-destructive and rapid method for evaluating forage composition. The relationships between HS measurements taken on the ground and forage components obtained through harvest and chemical analysis at ground level were analyzed. The dataset in the orchard grass-dominated meadow field consisted of 200 samples from seven fields in three regions of Hokkaido, Japan, surveyed prior to the first grass harvest in May/June 2023. Overall, the 1D-CNN models showed better predictive accuracies for most parameters (BM, CP, and NDF) than standard PLS regressions. The 1D-CNN model demonstrated a good predictive accuracy ($R^2 = 0.950$) for BM, but less accurate predictions for concentrations of CP ($R^2 = 0.650$) and NDF ($R^2 = 0.506$). However, when the content in percentage was converted to standing mass (g/m²), high predictive accuracies in CP mass ($R^2 = 0.814$) and NDF mass ($R^2 = 0.837$) were achieved. These results are expected to contribute to the advancement of forage management by enabling rapid and accurate evaluation of forage components.

Introduction

In Hokkaido, Japan's largest feed-producing region, the environmental impact of excessive fertilizer application on grassland ecosystems has become a significant concern (Takeda 2001). In the meadow fields, issues such as weed invasion and soil degradation diminish the nutritional value of forage grasses, adversely affecting livestock health and productivity (Nishida 2002; Otsuka 1995). These factors also contribute to spatial variation in grass yield and forage composition. Grass forages, including orchardgrass (OG; *Dactylis glomerata* L.) and timothy (TY; *Phleum pratense* L.), along with legume forages such as white clover (WC; *Trifolium repens* L.), red clover (RC; *T. pratense* L.), and alfalfa (AL; *Medicago sativa* L.) are widely utilized in Hokkaido (Yamada 2009). Consequently, the rapid and accurate evaluation of the nutrient composition of these forages is essential for maintaining livestock health and productivity (Coleman and Moore 2003).

To address these challenges, remote sensing technology, using satellites and drones, has been increasingly employed as a diagnostic tool to evaluate grass resources and vegetation conditions across extensive areas quantitatively (Kawamura et al. 2012). Among these technologies, hyperspectral (HS) remote sensing technology, which measures continuous wavelengths in the visible to near-infrared (NIR) spectrum, has proven to be a powerful method for estimating the nutritional value of forages in the field (Zarco-Tejada 2000). Specifically, field HS measurements at canopy scale employs spectral analysis that is sensitive to the unique structural and chemical characteristics of these plant communities, allowing for the successful estimation of herbage biomass (BM), crude protein (CP), neutral detergent fiber (NDF), and other quality-related parameters (Lim 2016; Pullanagari et al. 2012).

In HS data processing and laboratory NIR spectroscopy, partial least squares (PLS) regression has been widely employed to estimate herbage BM and forage quality status (Marten et al. 1983). However, existing models are dataset-dependent and cannot be universally applied to different pastures. Therefore, it is necessary to develop a new model for each grassland (Fernández-Habas et al. 2022). In contrast, deep learning enables highly accurate estimation independent of data, allowing a single model to be applied to different meadow fields. Consequently, the objective of this study was to develop a nondestructive and rapid estimation model of herbage BM and forage nutritive status (CP and NDF) through deep learning by examining the relationship between field HS data and herbage BM or forage quality conducted prior to the first grass cutting in seven OG-dominated meadow fields in Hokkaido, Japan. In the present study, a one-dimensional convolutional neural network (1D-CNN) (Kawamura et al. 2021) was utilized for deep learning and compared with PLS.

Methods

Field surveys were conducted across seven meadow fields of OG-legume mixtures at three research institutions: (1) Obihiro University of Agriculture and Veterinary Medicine (OBH), (2) NARO Hokkaido Agricultural Research Center (HRC), and (3) Rakuno Gakuen University (RGU) in Hokkaido, Japan (Figure 1). Both RGU, located in Ebetsu City, and HRC, located in Sapporo City, are in a region characterized by a harsh, cold, and snowy climate. The Obihiro City area in Tokachi, while experiencing less snowfall than Sapporo and Ebetsu during winter, encounters lower temperatures. According to data from the Japan Meteorological Agency's Automated Meteorological Data Acquisition System (AMeDAS), the mean annual temperatures in 2023 were recorded as 10.95°C in Sapporo, 8.89°C in Ebetsu, and 7.16°C in Obihiro. Additionally, annual precipitation in these cities was recorded as 966, 965, and 919 mm, respectively.

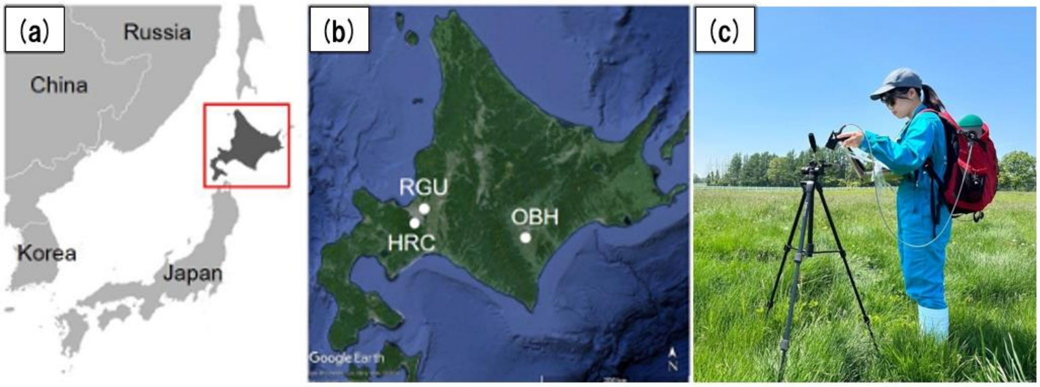

Fig 1 Location of Hokkaido, Japan (a) and three research institutions (b) with a photograph depicting the field HS measurement at HRC (c).

Field surveys were conducted between May 16 and May 29, 2023, during wich 200 samples were obtained. An ASD Fieldspec 4 Hi-Res spectroradiometer (Malvern Panalytical Ltd., UK) was employed to acquire field HS data (350–2500 nm). The sensor head was held approximately 50 cm above the canopy at the nadir position. The spectroradiometer had a 25° field of view (FOV), producing a view area with a 22 cm diameter at the canopy level.

Following the field HS measurements, grass height (5 points) was recorded and averaged as a surface sward height (SSH) within randomly placed quadrats (50 cm × 50 cm) in the field, and aboveground biomass was harvested at 0 cm above the ground surface. Grass samples were classified into five groups: OG, kentucky bluegrass (KB; *Poa pratensis* L.), legumes (WC + RC + AL), weeds, and dead materials, then dried in a dryer at 65°C for 72 hours and weighed for dry matter weight (g DM/m^2). Herbage BM was computed as the sum of the values for OG, KB, legumes, and weeds. Chemical analyses were then performed at the Federation of the Tokachi Agricultural Cooperative Association, Agricultural Product Chemical Research Laboratory.

Data preprocessing and PLS regression analyses were performed using Matlab software ver. 8.10 (MathWorks, Sherborn, MA, USA). In the development of the deep learning model, a one-dimensional convolutional neural network (1D-CNN) architecture was employed, which is suitable for one-dimensional spectral information. data set (n = 200) was sprit into training (80%, n = 160) and test (20%; n = 40) subsets. Then, the models were developed using training dataset, and the model accuracy was assessed using leave-one-out cross-validated R^2 and root mean squared error (RMSE). The predictive ability was evaluated using the test dataset.

Results

In PLS analyses, the cross-validated R^2 values indicated very low predictive accuracies (R^2= 0.095–0.266) andsubstantial errors, as denoted by the RMSE for herbage BM (111.343 g DM/m^2), CP (3.665%), NDF (7.351%), CPmass (21.167 g DM/m^2), and NDFmass (72.439 g DM/m^2), respectively.

The 1D-CNN models exhibited superior predictive accuracies for most parameters compared to standard PLS regressions. Specifically, the 1D-CNN model demonstrated commendable predictive accuracy (R^2 = 0.950) for BM, although it yielded less accurate predictions for the concentrations of CP (R^2 = 0.650) and NDF (R^2 = 0.506). In contrast, when the percentage content was converted to standing mass (g/m^2), high predictive accuracies were achieved for CP mass (R^2 = 0.814) and NDF mass (R^2 = 0.837).

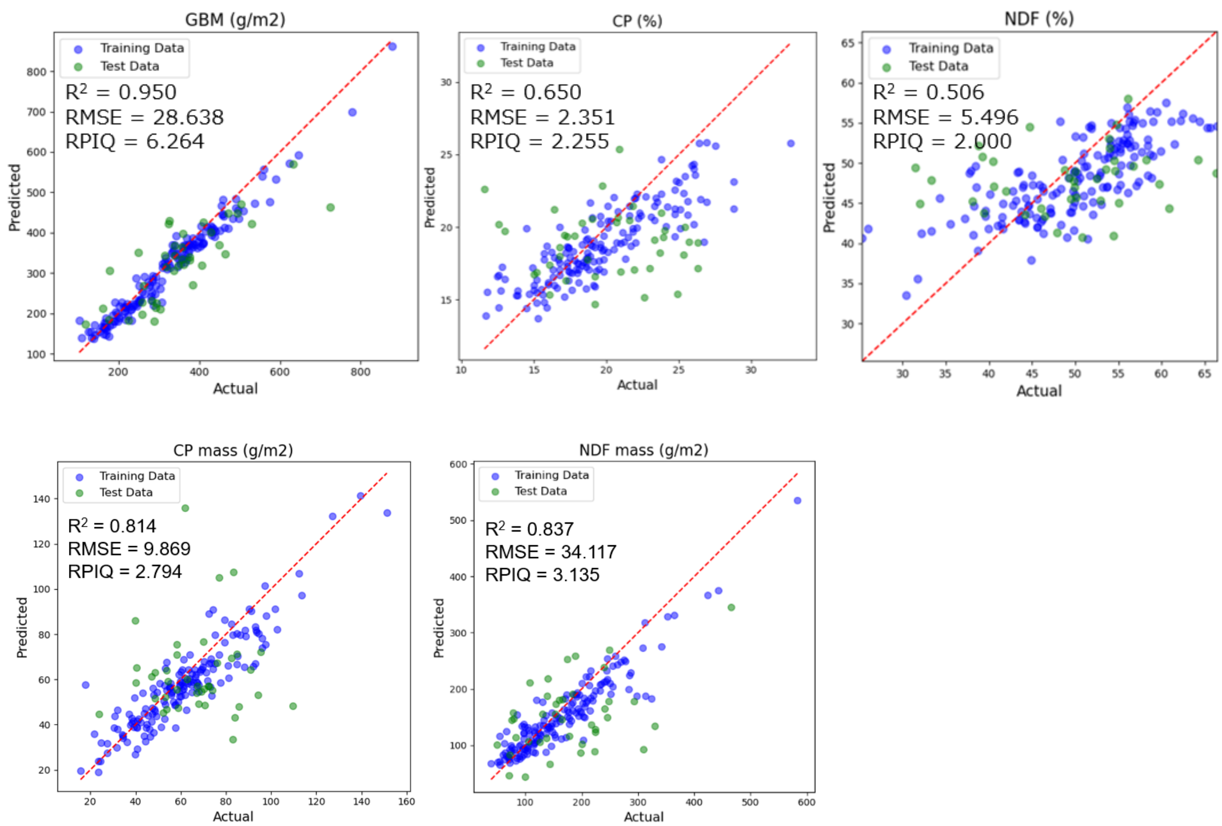

Fig 2 Relationships between observed- and predicted-values of herbage BM (a), CP content (b), NDF content (c), CP mass (d), and NDF mass (e).

Discussion

The PLS regression analysis conducted using the dataset collected from the seven fields did not exhibit the same level of estimation accuracy as observed in prior studies (Fernández-Habas et al. 2022). Conversely, the application of the 1D-CNN method from deep learning revealed a significant enhancement in predictive accuracy. Additionally, it has been suggested that the estimation accuracy for CP and NDF, which displayed low estimation performance, could be improved by converting these parameters into standing mass information.

These findings imply that the estimation accuracy can be enhanced through deep learning applied to the spectral data gathered from hyperspectral measurements utilizing 1D-CNN. Furthermore, the versatility of the model indicates its potential applicability across various fields. Moreover, given that the sensing data captures the surface reflectance of the plant community, it may be more advantageous to utilize standing mass over concentrations of CP or NDF.

In this investigation, we developed an estimation model to assess herbage BM and forage quality via deep learning from ground-based hyperspectral data. However, the dataset (n = 200) utilized in this study is relatively small in terms of data size for deep learning applications. Future efforts should focus on expanding the dataset to further enhance accuracy and versatility.

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