Impacts of Height and Density of Gramineous Plant Community on Internal Wind Speed—Toward Safety Assessments of TRU Waste Disposal—

Izuki Endo*†, Nobuyoshi Ishii**, Mizue Ohashi*, Kazuo Matsumoto*** and Shigeo Uchida**

*School of Human Science and Environment, the University of Hyogo.
1–1–12 Shinzaike-Honcho, Himeji-shi, Hyogo Pref. 670–0092, Japan
**National Institute for Quantum and Radiological Science and Technology, National Institute of Radiological Sciences, 4–9–1 Anagawa, Image-ku, Chiba-shi, Chiba Pref. 263–8555, Japan
***Faculty of Agriculture, University of the Ryukyus, 1 Senbaru, Nishiharacho, Nakagamigun, Okinawa Pref. 903–0213, Japan
†izok@shse.u-hyogo.ac.jp

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Radioactive carbon (14C) is the dominant radioactive nuclide in transuranic (TRU) waste. However, only a few studies to date have taken into account 14C transition in its gaseous form (14CO2). For an appropriate biosphere assessment of geological disposal, it is important to understand the degree of 14CO2 mixing with ambient air by vegetation. To evaluate the impacts of the structure of the plant community, relative to the vertical and horizontal wind speed, we characterized the structure of two gramineous plant communities (community-1, community-2) and compared the wind at three heights (middle, top, and above) of each community. The comparison of the two plant communities revealed that the biomass was the same, but the plant height of community-1 was 78% of that of community-2, and its vegetation density was approximately twice as high. Wind speeds of middle of the community with a higher vegetation density were less affected by the winds outside the community. It was assumed that the winds in the plant communities became more restricted as the community density increased. It is therefore suggested that effects of vegetation density are an important factor for the retention and the transition of 14CO2 to vegetation.

Key Words: Geological disposal, 14CO2, horizontal wind, vertical wind, vegetation density

1. Introduction

Transuranic (TRU) waste is generated during the processing of mixed oxide (MOX) fuel and during nuclear fuel reprocessing. Many kinds of radioactive nuclides are contained in TRU waste.1 TRU waste is generally disposed to bedrock more than 300 m below ground. Radioactive carbon (14C) is one of the elements contaminating TRU waste, and it is found in the terminal part and in fragments such as hulls and end-pieces, derived from the spent fuel assemblies.2 14C disintegrates through beta decay and its half-life is 5,730 years. 14C shows weak sorption onto natural barriers such as rocks; hence, there are concerns regarding the release of 14C, in its dissolved form, to ground surfaces associated with groundwater movement,3 from where it could be taken up into the water cycle and in the biosphere. Furthermore, in ground surfaces, part of the dissolved 14C would be utilized by microorganisms and may convert
into a gaseous form. Research on $^{14}$C behavior in rice-paddy field soils demonstrated that more than 60% of $^{14}$C was released into the air as gaseous compounds, mainly $^{14}$CO$_2$. $^{14}$C can be easily taken up by living organisms, including humans. In addition, Study report on TRU waste disposal technology indicated that $^{14}$C has the second highest contribution to dose, in an assessment of 10,000 years after geological disposal. Therefore, there is a need to evaluate the effects of $^{14}$C on humans after it has been discharged to ground surfaces. However, very few studies have evaluated the transition processes of $^{14}$C in the gaseous form; rather, more attention has been paid to $^{14}$C transition by dissolved form.

Gaseous $^{14}$C, released in ground surfaces, would be taken up by vegetation via $^{14}$CO$_2$ assimilation. The diffusion of CO$_2$ in the air is dependent on turbulence. Turbulence transports CO$_2$ in the vertical direction by mixing the air inside and outside the vegetation. Essentially, should there be a large downward wind as well as a large upward wind, turbulence is considered to be an eddy. Therefore, when the wind speed increases in various directions and turbulence develops, the air can be diffused more easily. Turbulence could thus affect the release and intake of $^{14}$CO$_2$ by vegetation. The magnitude of turbulence changes according to the structure of the plant community, such as plant height and density, which in turn changes the wind speed. Consequently, the effects of plant community structure on wind speed are important factors to be considered when performing safety assessments on the transition of $^{14}$CO$_2$ to vegetation.

Rice is cultivated on large sections of arable land in Japan. The form of gramineous plant bodies differs greatly from other agricultural crops, which may affect wind speed. In this study, we aimed at assessing the impacts of the plant-community structure on horizontal and vertical wind speeds. For this purpose, we compared the wind speeds among three measurement heights for two gramineous plant communities, which had different plant heights and vegetation densities, but an equal biomass. To the best of our knowledge, there has been no description in biosphere assessment reports considering the vegetation and the agricultural method after a period of 10,000 years. As these circumstances include large uncertainty, we assume that after a period of 10,000 years is as the same as present in this paper.

2. Experimental

2-1 Location of the data collection site

Wind speed data was recorded at the National Institute for Quantum and Radiological Science and Technology, in the National Institute of Radiological Sciences in Chiba City, Japan. Two study locations of herbaceous plant communities (community-1, community-2) were selected to study the effects of community structure on wind turbulence. These communities were at a distance of several tens of meters from each other.

2-2 Characterization of plant community structures

Each plant community was about 4m×2m in area. The highest point was on average 57 cm in community-1 and 70 cm in community-2. The herbaceous plant communities were both gramineous, but the specific species were unknown. Quadrats of 25 cm×25 cm (0.06 m$^2$) were placed in each community to characterize the community structure. We obtained the biomass, leaf area index (LAI), plant height, and vegetation-density data as indices of the community structure. To obtain the biomass data, the gramineous plants in the quadrat were harvested close to the ground. The weights of the freshly harvested samples were measured and converted into biomass (kg fresh weight·m$^{-2}$). Then three individual plants were taken out at random from the harvested samples, and their height (cm) was measured with a measuring tape, after straightening...
each leaf from bottom to tip. The vegetation density (plant number·m$^{-2}$) was calculated by the number of plants grown per unit area; the number of plants grown in the quadrat was calculated by dividing the fresh weight of the harvested samples with the average weight of the three samples. Afterwards, the number of the plants grown in the quadrat was divided by the area of the quadrat and converted into a per-square-meter unit. To compare the aboveground coverage of the two communities, LAI was measured as follows. First, the leaves and stems of the same three samples were cut, pasted on paper, and imaged using a copy machine. Then the area of the leaves and stems was analyzed using ImageJ software. The LAI was calculated by multiplying the average area of a plant with the number of plants grown in the unit area.

2.3 Wind-speed measurements

Wind-speed data were obtained for each community during three days of October 2015. The weather during all three days was relatively stable. Measurements began in the afternoon and lasted for about 24 h. The wind speed was measured using an ultrasonic anemometer (DS-2 Sonic Anemometer, Decagon Devices). The ultrasonic anemometer reports wind speed with a resolution of 0.01 m·s$^{-1}$. Wind speeds below the detection limit were recorded as 0 m·s$^{-1}$ in the north direction and the values were used as data. Data were recorded at 1-minute intervals using the data logger Em50 (Decagon Devices).

Measurements were conducted approximately in the center part of each plant community to minimize the effects of the edges of the plant community. Anemometers were set at three heights among the plant community. The lowest at 20 cm from the ground surface, which was inside the community (middle). The second to highest was set at the highest point (on average) in each community (top), which were 57 cm in community-1 and 70 cm in community-2. Finally, the highest anemometer was set at 126 cm from the ground, which was above the vegetation height of both communities (above). Two anemometers were placed at each measurement height, measuring the horizontal and vertical direction of the wind respectively. The horizontal wind was measured with the “N” mark on the anemometers facing the north direction. The vertical wind blowing from a certain direction was measured with “N” mark facing zenith direction.

2.4 Data analysis

To compare the structures of the two plant communities, Mann–Whitney $U$ tests were performed on

| Measurements                        | Community-1 | Community-2 | Statistical test |
|-------------------------------------|-------------|-------------|------------------|
| Mean $\pm$ SD $\pm$ n               | Mean $\pm$ SD $\pm$ n |            |
| Biomass (kg fresh weight·m$^{-2}$)  | 1.7         | 1           |                  |
| Leaf Area Index                     | 6.7         | 3           |                  |
| Plant height (cm)                   | 76          | 3           |                  |
| Vegetation density (plant number·m$^{-2}$) | 950         | 3           |                  |

Symbols in statistical test indicate significant differences between two plant communities ($\dagger$: Mann–Whitney $U$ test at $p<0.05$, *: $t$-test at $p<0.05$). SD; standard deviation, $n$; replicates.
Fig. 1 Time series of the horizontal wind speed at the different observation heights.

Fig. 2 Time series of the vertical wind speed at the different observation heights. The period during which there is a lack of data is blank.
Fig. 3  Comparison of the horizontal wind speed between the above and the top (A, B) and the middle (C, D) of the community.

Fig. 4  Comparison of the vertical wind speed between the above and the top (A, B) and the middle (C, D) of the community.
the plant heights. In addition, t-tests were performed on the LAI and the vegetation density. The time periods for the wind-speed correlation analysis were taken from 9:00 to the end of the measurement time for community-1 and from the start of the measurement time to 1:30 for community-2, for both the horizontal and vertical wind data. This was due to the fact that the wind inside the community fluctuated during these time periods. A Pearson’s product-moment correlation analysis was also performed using IBM SPSS Statistics 22.

3. Results

3.1 Comparison of the community structures

The biomass appeared to be the same in the two communities (Table 1). The LAI was slightly lower in community-2 but there were no significant differences in the LAI between the communities (Table 1). The plant height and vegetation density showed significant differences between the two communities. The plant height of community-1 was 78% of the height of community-2 (Table 1, \(p < 0.05\)) and the vegetation density was 2.1 times higher in community-1 compared to community-2 (Table 1, \(p < 0.05\)).

3.2 Time series of wind speeds

In community-1, the horizontal wind speed fluctuated at the above, top, and middle of the community, after 9:00 (Fig. 1-A, C, E). The range of the wind-speed fluctuation was largest in the above, smaller at the top, and smallest at the middle of the community. In community-2, horizontal wind speed fluctuation was also observed on every measurement height, from the start of the measurement to around 1:30 (Fig. 1-B, D, F). The wind-speed fluctuation range did not appear to depend on the structures of the communities.

Vertical wind speed fluctuation was also observed in both communities (Fig. 2), during the same time period as the horizontal wind data was gathered (Fig. 1). The magnitude of the vertical wind-speed fluctuation was largest in the above, smaller at the top, and smallest at the middle of both communities; trend data was as same as that for horizontal wind (Fig. 2).

3.3 Correlation analysis of wind speed

A positive correlation of the horizontal wind speed between the above, and the top or the middle of the community was observed in both communities (Fig. 3). The correlation coefficient between the above and the middle of the community was stronger in community-2 than in community-1 (Fig. 3-C, D). The ratio of above to middle (slope of the regression) was 0.016 in community-1 and 0.116 in community-2 (Fig. 3-C, D). The slope was smaller in community-1, as compared to community-2.

A positive correlation of the vertical wind speed between the above and the top of the community was observed in both communities. The correlation coefficient was stronger in community-2 than in community-1 (Fig. 4-A, B). There was no correlation between the above and the middle of community-1 (Fig. 4-C), but a weak positive correlation was observed in community-2 (Fig. 4-D).

4. Discussion and concluding remarks

The wind speed comparison between the two plant communities suggested that the difference in community structure influenced the wind speed inside the plant community. Correlation analysis revealed that even though there was a positive correlation between horizontal wind speed in the above and the middle in both communities, the slope of regression (the ratio of the above to the middle) was smaller in community-1 compared to community-2 (Fig. 3-C, D). This indicates that the horizontal wind speed inside the vegetation is not affected much by the wind speed in the above. In addition, correlation analysis also revealed that the vertical wind speed inside
community-1 was not affected by the wind speed in the above of the community, whereas the vertical wind speed inside community-2 was affected (Fig. 4-C, D). A comparison of the structure of the two communities indicated that in community-1 the plant height was lower, and the vegetation denser, than in community-2 (Table 1). For a vegetated surface, gas exchanges occur most actively when the vegetation density is relatively low. Conversely, if the vegetation density is high, the wind cannot enter the vegetation as easily. On the other hand, in forests with significant tree height, the wind speed may be different in the crown compared to the trunk space. Watanabe pointed out an increase in wind speed within the trunk space when studying the wind profile within the canopy. Nevertheless, as in the case of grassland, the leaves in the plant community examined herein were normally distributed from the surface to the ground, without gaps. Studies have also shown that wind speed declines exponentially, starting from the community surface. Thus, unlike in forests, the wind speed in herbaceous plant communities is not considered to be affected by plant height; instead, vegetation density is thought to have a greater effect on the wind speed inside the community. Our results indicate that denser vegetation may prevent wind speed from propagating from the outside to the inside of the community.

Generally, the horizontal wind speed increases logarithmically from the surface of the vegetation to the above part. In this study, the wind speed in the above part was measured at a height of 69 cm (community-1) and 56 cm (community-2) above the vegetation surface. These heights are affected by the resistance caused by the interaction between the air and the vegetation surface. During measurement, the mean horizontal wind speed in the above part was $0.64 \pm 0.61 \text{ m s}^{-1}$ (mean $\pm$ S.D., $n=1432$) in community-1, and $0.72 \pm 0.42 \text{ m s}^{-1}$ (mean $\pm$ S.D., $n=1350$) in community-2. There appeared to be a difference in mean wind speed between the two communities. The slope of regression in community-1 was about $1/7$ of the slope of regression in community-2 (Fig. 3-C, D), suggesting that the wind inside the plant community is less affected by the wind outside the community, when vegetation density is high. In order for this resistance to be negligible, measurements should be taken at a sufficient distance from the vegetation surface. This could be a topic for future study.

The mixing of $^{14}\text{CO}_2$ inside and outside the vegetation will be greatly influenced by the turbulence at the interface between the community and the ambient air. This suggests that dense vegetation may affect the retention of $^{14}\text{CO}_2$ inside the plant community. It is important to note that community structures will change over time. The density of the aerial parts of the rice plants, particularly, increases drastically based on its tiller characteristics. Furthermore, agricultural plant community structure at the time of generative growth, or during harvest season, is in fact likely to affect the intake of $^{14}\text{CO}_2$ from the inside of the plant community. Therefore, in order to evaluate the transition of gaseous $^{14}\text{C}$ into the plant, it is necessary to first understand the annual fluctuation of $^{14}\text{CO}_2$ between the plant community and the ambient air.

In this study, we compared wind speeds at three measurement heights in a community of gramineous herbaceous plants. Our results suggest that dense vegetation may prevent wind from propagating inside the plant community. From this point of view, when conducting geological-disposal safety assessments, it is necessary to take the effects of the vegetation community structure into account. Further studies are needed to better understand how the community structure affects wind speed and direction depending on the plant’s growth stage.

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要旨

イネ科草本植物の群落構造が群落内の風速に与える影響—TRU廃棄物処理における安全評価にむけて—遠藤いず美*†, 石井伸昌**, 松本一雄**, 内田滋夫**, 石井伸昌*, 大橋瑞江*, 松本一雄**, 内田滋夫**: *兵庫県立大学環境人間学部, 670-0092 兵庫県姫路市新在家本町1-1-12, **量子科
学技術研究開発機構，263-8555 千葉県千葉市稲毛区
穴川4-9-1，*** 琉球大学農学部，沖縄県那覇市那原
町千原1，izok@shse.u-hyogo.ac.jp

TRU廃棄物の地層処分生物群評価において，気体の
14Cの植物体への移行が考慮されていない。気体の
混合に寄与する風を評価するため，2つのイネ科植物
群落の3測定高で風速を測定した。両群落のバイオ
マスは同じだったが，群落-2に比べて群落-1の草丈
は78%であり，群落密度は2倍だった。群落上に対
する群落内の風速は密な群落（群落-1）で制限され
た。群落密度が群落内気体の滞留および植物への
14Cの移行に影響することが示唆された。

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