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Hydrological setting of infertile species-rich wetland——a case study in the warm temperate Japan

Kikuchi, A.[1], Nakagoshi, N.[1], Onda, Y.[2]

(1. Graduate School for International Development and Cooperation, Hiroshima University. Higashi-Hiroshima City, 739—8529 Japan. E-mail: kikuchi@hiroshima-u.ac.jp; 2. Institute of Geoscience, University of Tsukuba, Ibaraki 305—8571, Japan)

Abstract: The detailed groundwater flow and water chemistry to illustrate landscape structure of the infertile peatless mire by using piezometers and groundwater wells were measured. The instruments were installed in lines through a small spring-fed wetland underlying little peat from the hillslope to the valley bottom in southwestern Japan. Flow net and *EC* data clearly indicated that the wetland was situated in a high-*EC* groundwater upspring area. The low-productivity graminous vegetation was related with four hydrological factors such as: (1) high water level; (2) low-*EC* (< 25 micro S/cm) groundwater; (3) weakly upward hydraulic gradient; and (4) overflowing of negatively pressured groundwater. In other words, the "old or deep groundwater" constructed the foundation of slope-wetland, and maintained the high groundwater level. In contrast, overflowing "youthful groundwater" is supplied from head of slope-wetland preferentially through the shallow substratum. The plant communities of the peatless mire in southwestern Japan are similar to those of raised bog in northern cool temperate Japan. There have been some reports verifying that the underlying mineral substrata of such wetlands were quartzile rocks such as granite, rhyolite, chart and well-leached sand. Results showed (1) low cation availability affects the water acidity; (2) upward seepage of high-EC groundwater composed the foundation of the investigated peatless mire; and (3) the poor mineral condition seems to play a similar role to northern ombrotrophic(rain-fed) condition.

Keywords: eco-hydrology; electrical conductivity; groundwater flow; plant community; wetland

Introduction

The peatless mire(Wolejko, 1986; Fig.1a) is decreasing extensively due to the abandonment of traditional management, inflow of the wasted water, fire, mowing, reclaiming and other artificial impacts in the modern landscape of southwestern Japan(Fujiwara, 1979). Mire of this type is now of primary importance for nature conservation(e.g. NACS-J & WWF Japan 1996). However, despite of the concerns and attention given for their conservation, restoration and even re-creation(Kikuchi, 1991), most of the studies conducted are based on phytosociological (Fujiwara, 1979; Hada, 1984; Senuma, 1998) and geomorphological observations.

A peatless mire is characterized by vegetation with low coverage, absence of Sphagnum species, and a wide spread distribution of Rhynchosporetosum faberi and Rhynchosporetosum ruburae of Rhynchosporetum chinensis. The soil condition is usually sandy or deeply weathered granite or rhyolite without any kind of peat(Hada, 1984). According to Sakaguchi (Sakaguchi, 1961) and Suzuki(Suzuki, 1977), the isotherm of 25 degrees of the mean air temperature of July approximately coincides with the southern limit of the intensive peat accumulation. Thus, the peatless mire is limited below 450 m above sea level in western Honshu Island(Hada, 1984), other southwestern lowland and islands of Japan.

While climate controls the major regional wetland zones(Fig.1a), the internal differentiation of the mire is determined by hydrological and hydrochemical conditions that are strongly associated with the topography and geology of the area(Wolejko, 1986). Understanding of hydrological factors determining the natural development of the peatless mire may provide clues on how to tackle restoration or recreation elsewhere. Hydrological and hydrochemical relations with the surrounding landscape are of primary importance in this respect(Boeye, 1994).

In this paper we focused on the ecological implications of the natural hydrological system, notably the effect of the groundwater discharge directly related to the vegetation. We investigated whether the infertile herb species-rich community occurs under influences of the upward seepage in the peatless mire.

1 Study site and methods

1.1 Study site

The study area is located in central Japan (34.4°N, 137.3°E: Fig. 1-a). There is a lot of small peatless mire in Mino-Mikawa area (Fig.1a) and their density varied by substrata. Most of investigated site were observed in the gravel and sand with thin clay stratum area(Senuma, 1998). In the investigated area(Fig.1c), there are hills of 150—200 m above sea level that are underlying in two types of substrata that sharply contact with each other: gravel and sand with thin clay strata (quaternary fluvial deposits) in the northern part, and a weathered granite in the southern part. Although secondary forest such as *Pinus densiflora* and *Quercus serrata* community are predominant on the northern area, the former is more widely distributed that depends on unfavorable ecological conditions such as poor soil condition. Some peatless mire develops on sites where water is oozing in such pine forest area at the valley bottom and at the lower part of hillside slope.

1.2 Vegetation analysis

The study sites consisted of transects that started from the point X on the valley bottom and extended to the point X' approximately 5m inside the forest on side slope through infertile herb species-rich community(Fig.1c). The two belt transects ($X1$ and $X2$) were lined close along both side of the transect X-X', whose length was 19m. The area of each quadrat was 1m by 1m. There were 38 plots in total. In the second week of September 1998, we investigated the herb layer vegetation(< 1m) according to the presence/absence of species. The data was classified by two-way indicator species analysis(Hill, 1979a), that is, TWINSPAN from the Cornell Ecology Program Series in PC-ORD Version 4 of MjM Software Design using the default options, except for the pseudo-species cut levels, which were set to 0, i.e. presence/absence. Ordination was done by using multiple method of Detrended Correspondence Analysis(Hill, 1979b), that is a modified version of DECORANA from the Cornell Ecology Program Series in PC-ORD Version 4 of MjM Software Design using the default options, except for the down weight rare species.

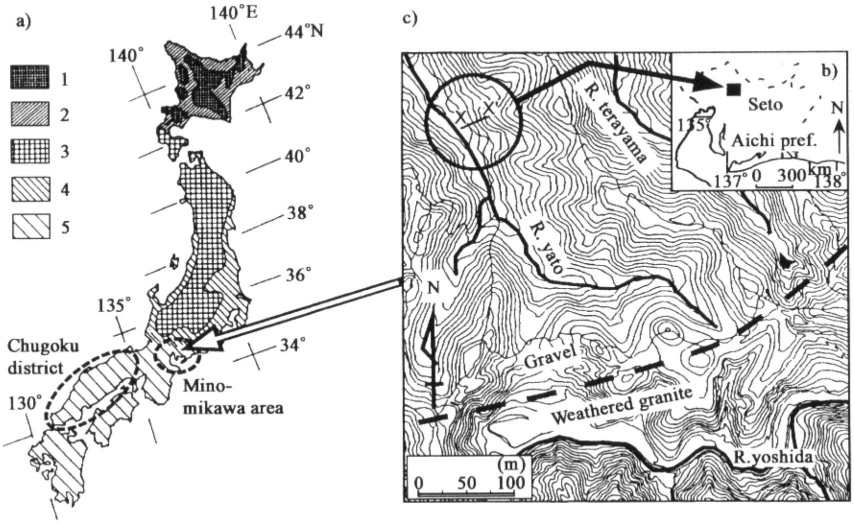


Fig.1 a. Climatic mire zones in Japan: 1. mountain mire zone of Hokkaido; 2. lowland bog zone of Hokkaido; 3. moutain mire and upland bog zone of northern Honshu; 4. transitional zone; 5. peatless mire zone of southern Japan(Wolejko, 1986). Study site is a natural oligotrophic wetlands without peat in Seto area, central Japan. The Chugoku district is the area investigated by Hada(Hada, 1984), the Mino-Mikawa area is investigated by Senuma (Senuma, 1998). b. Map of investigated area in Aichi prefecture. c. Topographical map of the investigation site. The contour lines are underlined every 2m. Circled area in the map is the investigated slope-wetland. There were two belt transects, 47 piezometers, and 11 wells along the transect *X*-*X′*

1.3 Hydrological analysis

A total 47 piezometers and 11 wells along the transect were laid out. The hand-driven piezometers in soil were made of plastic polyvinyl chloride(PVC) casing with an inside diameter of 2 cm and a wall thickness of 3 mm. Water enters the piezometers through the open bottom. Water levels in the piezometers were measured by an electronic probe on the 9 September 1998 as data set of common period. The relative heights of the water levels were then determined by subtracting the depth to water from the top of each piezometer. The height of the water table was determined by well or the shortest piezometer. The pH and the electrical conductivity(*EC*) were also measured directly in the field with a pH/temperature and an *EC*/temperature probe at the same time. The measured data were converted to new data point which kept up with each vegetation quadrat along transect by the inverse distance algorithm (SigmaPlot, Jandel Scientific, weight 3).

2 Results

2.1 Vegetation

TWINSPAN classification of the belt transect data yielded four vegetation types, graminoids dominating vegetation (A), graminoids dominating shrubby vegetation (B), fern dominating scrub (C) and pine-juniper dominating forest (D) in two-way ordered (Fig. 4a). The most distinctive vegetation type (A) occurred in the center of wetland, which contained a large assemblage of small herbaceous plants(e.g. *Rhynchospora alba*, *Eriocaulon decemflorum* var *nipponicum*) and insectivorous plants (*Drosera rotundifolia*, *Utricularia bifida* and *Utricularia caerulea*) that were restricted to these stands. The most infertile site was the *Rhynchospora faberi*, a dominant community (A′). The surrounding forest were first classified into Pine-juniper dominant forest (D), characterized by lack of graminoids and existence of *Eurya japonica* and *Pieris japonica*, which are component species of Pinus densifrora secondary forest. Graminoids dominating shrubby vegetation (B) and fern dominating scrub (C) were in contrast best distinguished by changes in the relative species composition. The vegetation types defined in TWINSPAN classification was also distinguished by separate DCA ordination of the vascular plant and Sphagnum data (Fig.2).

2.2 Groundwater level and hydraulic gradient of the plant communities

The differences and well-ordered pattern of vegetation (Fig. 2) seemed to reflect the groundwater condition. Thus the

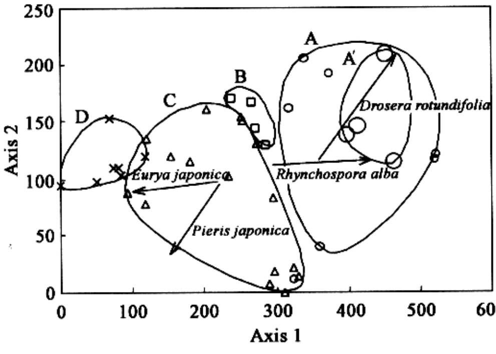


Fig.2 A scatter disgram of the 38 stands for the first two axes of DCA plot ordination
Small ○. Graminoids dominating vegetation (A); large ○. Especially infertile area(A′); □. Graminoids dominating shrubby vegetation(B); △. Fern dominating scrub(C); × pine-juniper dominating forest(D). These were classified by TWINSPAM in two-way order(see appendix). Vectors are superimposed for the DCA score of each indicator species that were used in TWINSPAN from the center of gravity. *R. alba* is the indicator species at the first level TWINSDPAN division, *D. rotundifolia*, *E. japonica* and *P. japonica* for the second level division. Spatial distribution of these vegetation types is in Fig.4a

variation in vegetation types were analyzed in relation between the groundwater level (aeration) and shallow hydraulic gradient (spring; Fig.3). At low groundwater level condition(< 20 cm), pine-juniper dominating forest (D) correlated positively with hydraulic gradient. In contrast, fern dominating scrub(C) was correlated with negative hydraulic gradient. At the intermediate groundwater levels in the vicinity of – 10 cm, hydraulic gradient of the fern dominating scrub(C) and graminoids dominating shrubby vegetation(B) changed into positive, and it was larger in the former than the latter. At high groundwater level near the ground surface(> – 10 cm), graminoids dominating vegetation(A) had its position around zero in hydraulic gradient. In this paper, we made a working hypothesis that the low-productive herbaceous community would occur under influences of the upward seepage. It is certain that there was positive hydraulic gradient at graminoids dominating shrubby vegetation(B) on the vicinity of – 10 cm groundwater level. On the contrary, infertile vegetation were not associated with specific gradient on the highest groundwater level above – 5 cm. This applied to hydraulic gradient just around zero at the *Rhynchospora fujiianae* dominating variant (A′).

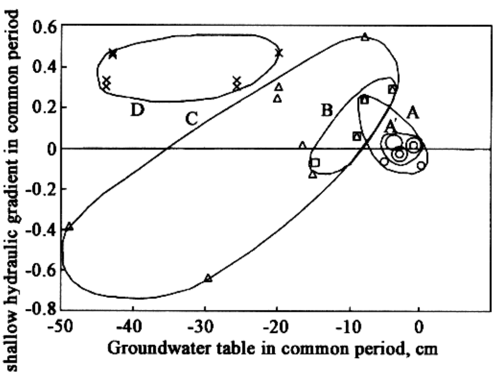
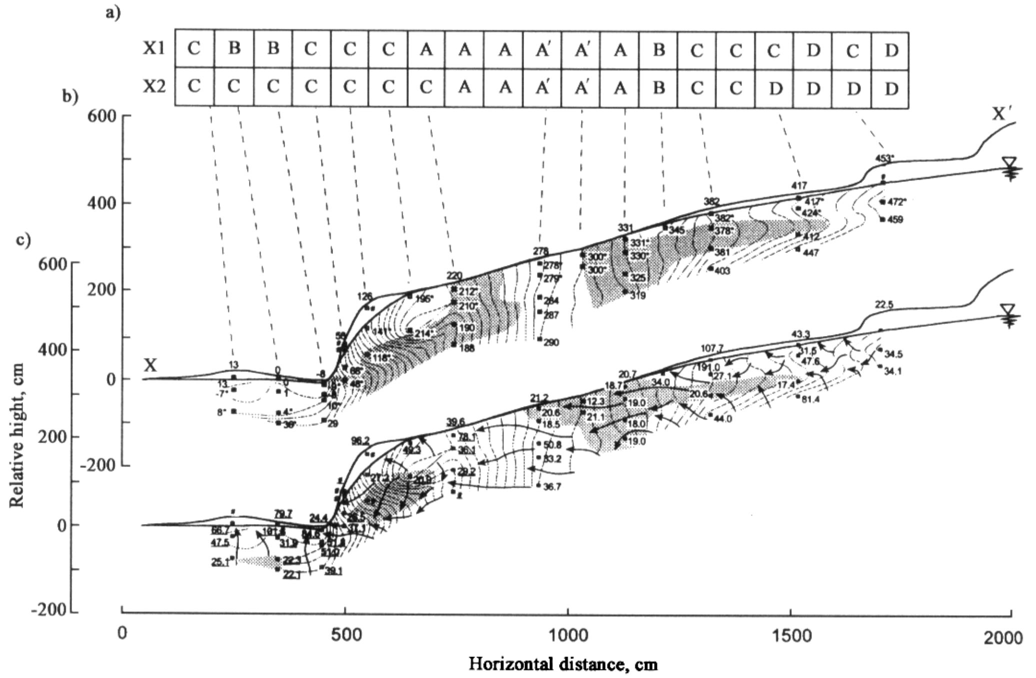


Fig.3 The bivariate plot of groundwater level vs. shallow hydraulic gradient in the common period. All symbols correspond to those of Fig.2. Hydraulic gradient was calculated between two shallow hydraulic head with asterisk in Fig.4b at each piezometer nest. The data were converted to new data point which kept up with each vegetation quadrat along transect *X-X′* by the inverse distance algorithm (SigmaPlot, Jandel Scientific, weight 3)

2.3 Hydraulic regime and infertile vegetation

If the water level in piezometers is lower than a groundwater level, it means that the water pressure is lower than atmospheric pressure at the bottom of the piezometer. Groundwater leaks towards the lower area than groundwater level in such case. The area is shown in Fig.4b. Conversely, if the water in the deeper piezometer rises upper than the groundwater level, the pressure is higher and the groundwater flows upward having the potential of ooziness. Such area is left uncolored in Fig.4b.



X1	C	B	B	C	C	C	A	A	A	A′	A′	A	B	C	C	C	D	C	D
X2	C	C	C	C	C	C	C	A	A	A′	A′	A	B	C	C	D	D	D	D

Fig.4 a. A spatial distribution of vegetation types. All symbols correspond to those of Fig.2. b. Hydraulic head(cm) distribution along transect *X-X′* (in Fig.1c). Dashed lines are extrapolated beyond 10 cm. The water level is assumed to be at very close to the ground surface in the center part. The meshed parts are negative pressurized groundwater than the atmospheric pressure. Two shallow values with asterisk at each piezometer nest were used for calculating of hydraulic gradient. c. The electric conductivity (*EC*) distribution and groundwater flow direction. Arrows represent direction of fine-scale groundwater flow. The meshed parts are low-*EC*(< 25 micro S/cm) groundwater. The values with under line were measured with pH. Because of equipment problems, there are no data at the piezometer and wells installed on the upper part from a center. Values above the ground are the data measured from well

The gradient in hydraulic head clearly indicated that the wetland was situated in a groundwater upspring zone(Fig.4b). The groundwater flowed upward at the bottomland and the upper wetland, then reached groundwater level. The upspring groundwater also reached to the ground surface at the center of slope-wetland but its direction was gentle. The infertile vegetation was on this central slightly upspring area.

Furthermore, there were two areas of negative pressured groundwater that made the groundwater flow pattern complicated. First, the negative pressured groundwater flowed sideways as converging groundwater flowing through the shallow substratum in the upper wetland. Then, it stretched and faded away at the center of the wetland with a divergent flow. This water moved and soon infiltrated the soil after performing the approximately 1m positive pressured shallow tracks at the center of the wetland and flowed through the negatively pressured area. Consequently, it converged and flowed out at the toe of the wetland.

Fig.4c is a cross-section showing the distribution of groundwater *EC*. To trace the groundwater that associated with infertile vegetation, we established a groundwater type smaller than 25 micro S/cm, as shown in Fig.4c. There were three areas among low-*EC*(< 25 micro S/cm) groundwater. The biggest one corresponded with the area of negative pressured water at the upper part of slope-wetland. This low-*EC* groundwater flowed from the bottom of the negative pressured area horizontally and then stretched accompanying groundwater flow to the surface where infertile wet vegetation occurred.

On the other hand, the electric conductivity in logarithmic scale was positively associated with pH(multiple $r = 0.645$, $r^2 = 0.417$, $p = 0.00066$, with hydrogen ions subtracted (Sjors, 1950): multiple $r = 0.685$, $r^2 = 0.469$, $p = 0.00022$). The low-*EC* groundwater(12.3 to 25 micro S/cm) was estimated that the pH was 4.8 to 5.2 by the former equation.

3 Discussion

3.1 Setting of infertile species-rich vegetation

Shimoda(Shimoda, 1979) pointed out that the unproductive plant communities found at the center of peatless mire resembles to raised mire(bog) in species composition because of the presence of the following same genera: *Rhynchospora*, *Eriocaulon*, *Utricularia* and same species: *Moliniopsis japonica*, *Rhynchospora alba*, *Eleocharis wichurae*, *Drosera rotundifolia*, and *Carex omiana*. In the less productive area of the peatless mire, *Rhynchospora chinensis-Eriocaulon sikokiana* community corresponding to Rhynchosporretum chinensis was found(Hada, 1984). In addition, in their study they compared the associations of raised mire (bog) to peatless mire based on these three hollow communities: *Eriocauletum kushiroensis*, *Eriophoro monoccoccon-Sphagnetum dusenii*, and *Eriocauletum dimorphoelytri* of Moliniopsio-Rhynchosporion albae(Miyawaki, 1970).

The less productive part of peatless mire could never be classified as raised mire(bog), because of little peat and lack of sphagnum species. The phytosociological similarity that Shimoda(Shimoda, 1979) represented may suggest that peatless mire has a similar ecological feature to ombrotrophic(rain-fed) wetland. Such phenomena are also found in southern mountain fens in USA(Moorhead, 1998). Many fens of southern mountain have both characteristics of fen and bogs. Since they receive groundwater inputs from surrounding mineral soils, they should be classified as fens. Bridgham *et al*. (Bridgham, 1996) suggested that the term "bog" and "fen" be used colloquially to describe sites based on vegetation, alkalinity, and acidity, irrespective of hydrology(rain-fed or groundwater-fed).

As far as mire was concerned, a bimodal frequency distribution of water pH was observed in our study. One mode(< pH 5.0) appeared to represent water buffered by humic material in bog and poor fen, the other(> pH 6.0) represented to water buffered by the bicarbonate system(Refer to the following section) in rich fen(Sjore, 1950; Gorham, 1992). Our data showed that investigated infertile vegetation(*A'*) corresponded with groundwater characterized by *EC* 12.8 to 25(micro S/cm) and pH 4.8 to 5.2(the estimated values). Our data on peatless mire corresponded to the upper limit of acidic mire ecosystem.

3.2 Background of hydrochemical regime

Infiltrated groundwater (youthful water) is hydrochemically related to rain water with low-*EC* (< 5 micro S/cm). Atmospheric precipitation saturated by carbon dioxide passes though the biological activity zone and become pH 5.5 after getting hydrochemical processes in the soil. The groundwater is chemically enriched dissolving of minerals from the soil layers. With growing residence time the *EC* and cations concentration increase(Hem, 1970). Taking the ion balance into account, it can be concluded that the dominant Ca^{2+} -ion is counter balanced by the dominant HCO_3^- -ion which means that calcite-like minerals in the subsoil play an important role and the CO_2^- pressure interfaces with the pH and HCO_3^- -ion of the groundwater (Kemmers, 1986).

Moreover, in order to evaluate the acidification or alkalization of soil and water, it would be necessary to distinguish between intensity and capacity factors. Intensity factors are determined by system that are considered. In contrast, capacity factors are a function of quantity or size of the system. For instance, the way of groundwater flow(the tendency to donate or accept a proton) is an intensity factor, while the amount of acid or base present in a given system is a capacity factor.

3.3 Functional landscape structure of infertile wetland

Our flow net and *EC* data suggested two distinct sources of flow in the wetland: high-*EC* water(> 25 micro S/cm) and low-*EC*-water(< 25 micro S/cm). Especially the former was associated with infertile herb-rich vegetation with the highest water level(> − 4 cm). On the other hand, *EC* was significantly associated with pH. These suggest that the former type of groundwater may be considered as "older or deeper groundwater" while latter type would be considered as "youthful".

In the investigated site the high-*EC* up-spring water maintained the foundation of slope-wetland. The low-*EC* groundwater overflowed through the shallow soil and appeared for the surface at just central wetland. Here was the place where high groundwater level was kept and infertile wet vegetation (*A'*) occurred. At the head of wetland, a low-*EC* groundwater was discharged from the negatively pressured area like a sandwich between high-*EC* groundwater. As before-mentioned hydrochemical process, low-*EC* groundwater does not occur from high-*EC* groundwater. Therefore, we

Table 1 Biased distribution of spring-fed wetlands in favor of quartzile rock

Soil-forming rock	Number of investigated wetlands	
	Cyugoku district	Mino-Mikawa area
Granite area	57	3
Rhyolite area	20	–
Andesite lava area	5	–
Pliocene or Diluvial formation area	2	17
Quartz-porphyry area	1	–
Chert	–	1
Paleozoic formation area	0	0

considered that this groundwater was not generated by getting chemical change from high-*EC* groundwater but flowed preferentially through the substratum getting little substantial interaction with circumstance.

Next, we consider a capacity factor. It is known that peatless mire occurs more frequent in granite and in rhyolite areas, but not in area of Paleozoic formation in southwestern Honshu Island, Japan(Hada, 1984). It is also known that the wetlands have biased distribution in favor of Pliocene or Dilluvial formation, granite, and chart(Senuma, 1998) in lowland of Tokai area, central Japan(Table 1). These quartzile soil-forming rocks must be characterized by peculiarity of resistance to chemical weathering that means low ability of cation donation to groundwater. This is considered as a capacity factor.

Results showed that low cation availability of the soil-forming rock and the preferential discharging maintained the poor mineral groundwater that resembled to rainwater. This may be the reason why vegetation of the infertile peatless mire in southwestern Japan is most likely the same to that of northern ombrotrophic(rain-fed) wetlands.

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