

Fig. (2). Example of the Research about the Natural Environment of Rivers (RNER) geographic information system (GIS) data. Square polygons represent individual units. Confluence and single-flow units are defined as units adjacent to more than three other units and two other units, respectively. The central white polygon represents open water, and the other small polygons represent classified vegetation patches.

Pre-Specified Conditions

Data sets for river channel networks have a hierarchical construction: flows compose reaches, which link together to form larger stream networks (Lowe *et al.* 2006). Each of these components has unique traits. In addition, when a

large-scale data set such as the RNER data set is analysed, the power of statistical analyses is often influenced by variation among data collectors, data sampling dates, and non-investigated site characteristics (Link 1999; Link & Sauer 2002; Clark *et al.* 2003; Thogmartin *et al.* 2004). Additionally, environmental factors are usually spatially auto-

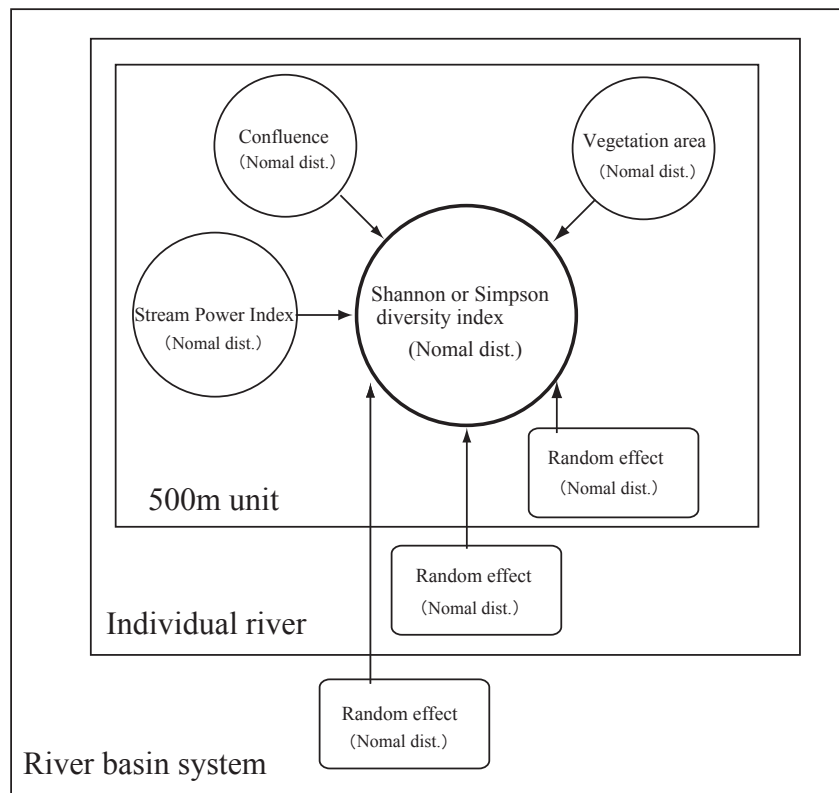


Fig. (3). Conceptual diagram of nested random effect models. The central circle represents the vegetation diversity index (patch number, Shannon H' , or Simpson D'). The surrounding circle represents fix effects, and the wavy square represents random effects.

correlated (e.g., Keitt *et al.* 2002). To minimise these issues, multiple types of random effects should be incorporated into models (Link & Sauer 2002). The use of random effects is an effective method for data summarisation; i.e., the reduction of many parameters into simple summaries (Link 1999). The top-ranked random effect used in our analysis was river basin systems, which are related to variation in river length, catchment area, landform, and other traits. The second-ranked random effect is individual rivers, which are related to the diversity of types and scales of human land use and artificial constructions. The bottom-ranked random effect is individual 500-m units, which are related to unobserved micro-environmental factors such as observer error. Our models incorporated a nested structure of these three random effects, which were treated as mean zero normal random variables (Fig. 3).

Model Establishment

We established hierarchical Bayesian models that included three hierarchical random effects. Shannon H' and Simpson D' were assumed to have normal distributions. Our models can be expressed as:

$$Y_{ijk} \sim \text{Normal}(\alpha_k, V),$$

$$\alpha_k = \text{Intercept} + \text{conf}_k + \text{SPI}_k + \text{area}_k + R_i + R_j + R_k, \text{ and}$$

$$V = \text{Variance of each diversity index},$$

where Y_{ijk} is Shannon H' or Simpson D' in a 500-m unit k on river j of river system i . We used the effects of three physical parameters as fixed effects: the presence of a river confluence (conf , 1, or 0); stream power index (SPI); and total vegetation area (area) of a unit. We also incorporated three random effects: river system, individual river, and individual unit (R_i , R_j , and R_k , respectively).

A necessary initial consideration in a Bayesian analysis is that prior distributions for each variable are informed (Link & Sauer 2002; Thogmartin *et al.* 2004). Because we had little empirical support for one distribution over another, our model was based on non-informative priors (Link & Sauer 2002; Thogmartin *et al.* 2004). All prior random and fixed effects were designed to have standard normal distributions (Fig. 3). Although we could not confirm normality of the two diversity indices in our data set using the Kolmogorov-Smirnov test (Shannon H' , p -value < 0.001; Simpson D' , p -value < 0.001), both indices did not have extreme dispersion (The means \pm SD of H' and D' were 1.09 ± 0.41 and 0.56 ± 0.19 , respectively) and histograms of both indices had one peak around the mean values. Thus, the variance of each prior diversity index distribution (V) was also designed to have a standard normal distribution.

Fitting the Hierarchical Model

To fit the hierarchical models, we used WinBUGS (The BUGS Project 2008) and R version 2.4.1 software (R Development Core Team 2008) with the R2WinBUGS package to conduct a Markov Chain Monte Carlo (MCMC) analysis using Gibbs sampling. To use the MCMC results, the Markov Chain must change from the initial values into a stationary distribution. We conducted MCMC sampling for 100,000 counts and discarded the initial 30,000 as burn-in. In addition, to minimise results affected by the initial values,

we conducted an analysis of three sets of initial values during MCMC sampling. We used R to generate random-sampling initial values and evaluated the contribution of fixed effects using a posterior predictive check based on a 95% confidence interval.

RESULTS

The means (\pm SD) of Shannon H' at confluence and single-flow units were 1.22 ± 0.32 and 1.07 ± 0.41 , respectively, and the means of Simpson D' at confluence and single-flow units were 0.62 ± 0.15 and 0.52 ± 0.20 , respectively. The mean values of SPI at confluence and single-flow units were 931.57 ± 808.00 and 631.11 ± 705.49 , respectively. The mean areas of vegetation in confluence and single-flow units were $103,106.8 \pm 53,742.2 \text{ m}^2$ and $90,994.7 \pm 62,312.0 \text{ m}^2$, respectively.

Our hierarchical Bayesian-model analysis revealed that all fixed effects had significant positive effects on Shannon H' (the 95% confidence interval did not include 0; Table 2). Simpson D' was positively affected by the presence of a confluence and area of vegetation but was not significantly affected by SPI (the 95% confidence interval included 0 for SPI; Table 3).

Table 2. Quantiles (2.5%, 50%, and 97.5%) of Posterior Distributions of Shannon Diversity Index (H')

Parameter	Mean	S.D	Values for the Following Percentiles		
			2.5%	50%	97.5%
Confluence	7.59×10^{-2}	2.50×10^{-2}	2.65×10^{-2}	7.61×10^{-2}	1.25×10^{-1}
SPI	4.10×10^{-5}	1.39×10^{-5}	1.38×10^{-5}	4.10×10^{-5}	6.83×10^{-5}
Vegetation area	1.27×10^{-6}	2.96×10^{-7}	6.82×10^{-7}	1.27×10^{-6}	1.84×10^{-6}
Deviance	-4.12×10^2	4.83×10^2	1.53×10^3	-3.37×10^2	3.04×10^2
Intercept	2.24×10^0	3.54×10^0	4.24×10^{-1}	6.37×10^{-1}	1.36×10^1

Table 3. Quantiles (2.5%, 50%, and 97.5%) of Posterior Distributions of Simpson Diversity Index (D')

Parameter	Mean	S.D	Values for the following percentiles		
			2.5%	50%	97.5%
Confluence	3.33×10^{-2}	1.27×10^{-2}	8.20×10^{-3}	3.33×10^{-2}	5.85×10^{-2}
SPI	1.32×10^{-5}	7.05×10^{-6}	-6.62×10^{-7}	1.32×10^{-5}	2.71×10^{-5}
Vegetation area	3.97×10^{-7}	1.53×10^{-7}	9.59×10^{-8}	3.98×10^{-7}	6.94×10^{-7}
Deviance	-2.38×10^3	2.58×10^2	-2.93×10^3	-2.36×10^3	-1.94×10^3
Intercept	1.15×10^0	1.06×10^1	2.55×10^{-1}	8.82×10^0	3.18×10^1

DISCUSSION

Our finding that confluence sites exhibited high vegetation-patch diversity in rivers in Hyogo Prefecture is the

first empirical support of the existence of confluence effects related to biological habitat diversity within riparian areas. Both the Shannon and Simpson diversity indices for vegetation patches were higher for confluence units than for single-flow units. Even though our results revealed a diversity pattern for roughly classified vegetation types, this type of pattern still provides a useful basis for investigating and understanding the process by which habitat diversity is maintained in riparian ecosystems.

Channel disturbances are amplified at confluences because these locations are points that accumulate water, sediments, and woody debris (Benda *et al.* 2004a; Benda *et al.* 2004b; Rice *et al.* 2006; Rice *et al.* 2008). Water movement can strongly affect the distribution of vegetation types throughout floodplains, as such forces alter the physical structure and stability of the habitat through erosion and sedimentation (Salo *et al.* 1986). Debris flows and sediment deposits result in topographic heterogeneity around river confluences (Benda *et al.* 2004b). Together with our results, these findings suggest that habitat diversity increases around river confluences because these areas have unique hydrodynamic features and subsequently amplify disturbance regimes. High habitat diversity generally corresponds to high diversity in plant species (Wagner *et al.* 2000). In fact, we found that plant species diversity was enhanced by the flooding-induced creation of bare ground around confluences of the river system in this study (Osawa *et al.* 2010). In turn, high plant diversity provides diverse habitats and food sources for animals (Qian & Ricklefs 2008). Thus, the highly diverse vegetation patches around river confluences may harbour many plant and animal species in river ecosystems. Future research should examine the detailed processes by which debris and sediment deposition and flooding disturbances enhance the establishment of diverse vegetation types and plant species.

In our analyses, we successfully regulated the effects of SPI and vegetation area in the models, and both factors affected vegetation diversity. For example, SPI positively affected the Shannon diversity index. SPI is conventionally used as an index of the erosive power of flowing water (Wilson & Gallant 2000) and can be used as a representation of disturbance intensity. Relatively strong disturbances likely occurred in high SPI areas, forming various types of vegetation patches, which points to the importance of

disturbance for habitat diversity. Vegetation area positively affected both the Shannon and Simpson indices. The RNER program was conducted throughout alluvial (from mid to downstream) river areas that were surrounded by mainly urban and/or agricultural areas (Hyogo Prefecture 2007). One possible explanation for the positive relationship between diversity indices and vegetation area is that smaller vegetation areas are indicative of the intensification of artificial habitat alterations.

To the best of our knowledge, our study is the first to demonstrate that river confluences may generate habitat diversity for plants in riparian areas, although the results should be interpreted with a little caution because of the failure of our data to meet some assumptions concerning normality of the diversity indices in the analyses. A linear perspective on river networks (i.e., the river continuum concept; Vannote *et al.* 1980) has dominated much of river ecology over the last 20 years (Fisher 1997), despite the recognition that river networks are branched with tributaries that interrupt gradual downstream changes in channel and valley morphology (Benda *et al.* 2004a). Recently, the network dynamics hypothesis has articulated the relationships among key attributes of river networks and the patchy heterogeneity of the fluvial process and form (Benda *et al.* 2004a; Benda *et al.* 2004b). Our results present empirical evidence of this more recent discontinuum perspective in river ecology, in which river confluences are considered key elements within a dendritic river network. Future research should examine confluence effects in a diversity of freshwater riverine systems (e.g. Fernandes *et al.* 2004), with particular focus on the fact that confluences vary in geomorphic features, such as shape and scale, within and among watersheds. Such variation in geomorphic features may produce different confluence effects on biodiversity (Benda *et al.* 2004b).

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Appendix

Appendix 1. List of Communities that Belong to each Vegetation Type in the RNER Data Set. All Scientific Names are Referred to YList, (http://bean.bio.chiba-u.jp/bgplants/ylist_main.html)

Vegetation type	Community name
<i>Miscanthus sacchariflorus</i> dominant vegetation	<i>Miscanthus sacchariflorus</i> community
<i>Phragmites communis</i> dominant vegetation	<i>Phragmites australis</i> community
<i>Phragmites japonica</i> dominant vegetation	<i>Phragmites japonica</i> community
<i>Salix gracilistyla</i> dominant vegetation	<i>Salix gracilistyla</i> community

(Appendix 1) Contd.....

Vegetation type	Community name
Floating-leaved and submerged plant vegetation	<i>Nymphoides peltata</i> community
	<i>Nymphoides indica</i> community
	<i>Potamogeton wrightii</i> community
	<i>Trapa japonica</i> community
	<i>Nuphar subintegerrima</i> community
	<i>Potamogeton octandrus</i> community
	<i>Potamogeton crispus</i> community
	<i>Hydrilla verticillata</i> community
	<i>Vallisneria natans</i> community
	<i>Potamogeton maackianus</i> community
	<i>Ranunculus nipponicus</i> community
	<i>Myriophyllum spicatum</i> community
	<i>Potamogeton oxyphyllus</i> community
	<i>Spirodela polyrhiza</i> and <i>Lemna aoukikusa</i> community
	<i>Egeria densa</i> and <i>Elodea nuttallii</i> community
	<i>Myriophyllum aquaticum</i> community
	<i>Pistia stratiotes</i> community
	<i>Eichhornia crassipes</i> community
<i>Azolla</i> spp.(exotic) community	
Halophytic plant vegetation	<i>Phacelurus latifolius</i> community
	<i>Aster tripolium</i> community
	<i>Carex scabrifolia</i> community
	<i>Limonium tetragonum</i> community
	<i>Suaeda australis</i> and <i>Atriplex gmelinii</i> community
<i>Artemisia fukudo</i> community	
Sand dune vegetation	<i>Carex pumila</i> community
	<i>Carex kobomugi</i> and <i>Wedelia prostrata</i> community
	<i>Scutellaria strigillosa</i> community
	<i>Calystegia soldanella</i> and <i>Lathyrus japonicus</i> community
<i>Vitex rotundifolia</i> community	
Vegetation beside mountain stream	<i>Hosta montana</i> community
	<i>Carex blepharicarpa</i> and <i>Osmunda lancea</i> community
	<i>Acorus gramineus</i> community
	<i>Carex curvicolis</i> and <i>Sedum subtile</i> community
	<i>Carex teinogyne</i> community
	<i>Carex persistens</i> community
	<i>Carex forficula</i> community
<i>Carex heterolepis</i> community	
Riparian forest vegetation	<i>Ulmus parvifolia</i> community
	<i>Celtis sinensis</i> and <i>Aphananthe aspera</i> community

(Appendix 1) Contd.....

Vegetation type	Community name
Riparian forest vegetation	<i>Juglans mandshurica</i> community
	<i>Melia azedarach</i> community
	<i>Zelkova serrata</i> and <i>Acer palmatum</i> community
	<i>Euptelea polyandra</i> community
	<i>Alnus japonica</i> community
Salix species dominant vegetation	<i>Salix chaenomeloides</i> and <i>Salix eriocarpa</i> community
	<i>Salix pierotii</i> community
	<i>Salix udensis</i> community
	<i>Salix miyabeana</i> community
	<i>Salix jessoensis</i> community
	<i>Salix triandra</i> community
Annual plant vegetation just beside river channel	<i>Lindernia procumbens</i> community
	<i>Persicaria lapathifolia</i> and <i>Panicum dichotomiflorum</i> community
	<i>Microstegium vimineum</i> community
	<i>Persicaria thunbergii</i> community
	<i>Persicaria hydropiper</i> community
	<i>Xanthium occidentale</i> and <i>Chenopodium ficifolium</i> community
	<i>Bidens pilosa</i> community
Low-moor vegetation	<i>Leersia japonica</i> community
	<i>Carex thunbergii</i> and <i>Isachne globosa</i> community
	<i>Leersia oryzoides</i> community
	<i>Eleocharis mamillata</i> community
	<i>Carex dispalata</i> community
	<i>Typha latifolia</i> and <i>Typha domingensis</i> community
	<i>Ischaemum aristatum</i> community
	<i>Phalaris arundinacea</i> and <i>Oenanthe javanica</i> community
	<i>Eleocharis kuroguwai</i> community
	<i>Leersia sayanuka</i> community
	<i>Schoenoplectus triqueter</i> community
	<i>Coix lacryma-jobi</i> community
	<i>Acorus calamus</i> community
	<i>Lycopus lucidus</i> community
	<i>Persicaria japonica</i> community
	<i>Penthorum chinense</i> community
	<i>Sparganium japonicum</i> community
	<i>Schoenoplectus tabernaemontani</i> community
	<i>Zizania latifolia</i> and <i>Bolboschoenus fluviatilis</i> community
	<i>Sparganium erectum</i> community
<i>Lythrum anceps</i> community	

(Appendix 1) Contd.....

Vegetation type	Community name
Low-moor vegetation	<i>Nasturtium officinale</i> community
	<i>Paspalum distichum</i> community
	<i>Iris pseudacorus</i> community
	<i>Alternanthera philoxeroides</i> community
	<i>Gymnocoronis spilanthoides</i> community
	<i>Cyperus eragrostis</i> community
	<i>Stachys aspera</i> community
	<i>Humulus scandens</i> and <i>Lactuca indica</i> community
	<i>Matteuccia struthiopteris</i> community
	<i>Phragmites vallatoria</i> community
	<i>Sambucus chinensis</i> community
	<i>Arundo donax</i> community
	Rudaceous grassland
<i>Potentilla chinensis</i> community	
<i>Artemisia capillaris</i> community	
Grassland vegetation on flood channel	<i>Fallopia japonica</i> community
	<i>Boehmeria nivea</i> community
	<i>Rumex japonicus</i> community
	<i>Miscanthus sinensis</i> community
	<i>Imperata cylindrica</i> and <i>Erigeron annuus</i> community
	<i>Glycine max</i> community
	<i>Arundinella hirta</i> community
	<i>Heracleum sphondylium</i> community
	<i>Digitaria ciliaris</i> community
	<i>Cayratia japonica</i> community
	<i>Boehmeria japonica</i> community
	<i>Artemisia indica</i> community
	<i>Sicyos angulatus</i> community
	<i>Verbena brasiliensis</i> community
	<i>Conyza sumatrensis</i> community
	<i>Artemisia indica</i> community
	<i>Coreopsis lanceolata</i> community
	<i>Ambrosia trifida</i> community
	<i>Festuca arundinacea</i> community
	<i>Helianthus tuberosus</i> community
	<i>Eragrostis curvula</i> community
	<i>Paspalum dilatatum</i> community
	<i>Fagopyrum dibotrys</i> community
	<i>Solidago altissima</i> community
<i>Sorghum halepense</i> community	
<i>Lolium multiflorum</i> community	

(Appendix 1) Contd.....

Vegetation type	Community name
Grassland vegetation on flood channel	<i>Crassocephalum crepidioides</i> community
	<i>Ipomoea triloba</i> community
	<i>Andropogon virginicus</i> community
Floodplain woody plant vegetation	<i>Deutzia crenata</i> community
	<i>Lycium chinense</i> community
	<i>Aralia elata</i> and <i>Rubus hirsutus</i> community
	<i>Rosa multiflora</i> community
	<i>Sasa palmata</i> community
	<i>Pleioblastus argenteostriatus</i> and <i>Pleioblastus shibuyanensis</i> community
	<i>Pleioblastus simonii</i> community
	<i>Pueraria lobata</i> community
Hill forest	<i>Ampelopsis glandulosa</i> community
	<i>Quercus acutissima</i> community
	<i>Quercus serrata</i> and <i>Quercus variabilis</i> community
	<i>Quercus aliena</i> community
	<i>Quercus glauca</i> community
	<i>Quercus phillyraeoides</i> community
	<i>Castanopsis cuspidata</i> and <i>Photinia glabra</i> community
	<i>Quercus myrsinifolia</i> community
Roadside weed vegetation	<i>Castanopsis sieboldii</i> community
	<i>Digitaria violascens</i> and <i>Eleusine indica</i> community
	<i>Eragrostis ferruginea</i> community
	<i>Cynodon dactylon</i> community
	<i>Pennisetum alopecuroides</i> community

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