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The Impact of Flood Frequency on the Heterogeneity of Floodplain Surface Soil Properties

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Abstract: Floodplain soils are subject to quasi-periodic flood disturbances. This flooding serves to enrich floodplain soils, increasing their fertility and often making them ideal locations for agriculture. However, what is less well understood is how the frequency of flooding impacts on soil fertility and the diversity of soil character. This study investigates how flood frequency influences the heterogeneity (assessed using 26 physical and geochemical soil properties) of floodplain soils in a semi-arid floodplain wetland system in New South Wales, Australia. The study includes an investigation of soil properties across four flood frequency (or disturbance frequency) categories ranging from frequent through to infrequent flood disturbance. Thirty samples were collected from each zone and the physical and geochemical soil data were analyzed using a suite of univariate and multivariate statistical tests. The results show that sites subject to an intermediate level of flood disturbance have a greater level of diversity in soil properties than those sites subject to frequent flood disturbances. These results reflect those of the Intermediate Disturbance Hypothesis, an ecological theory that posits the highest biological diversity will also be found in intermediately disturbed environments and suggests that there might be physical habitat drivers of biological diversity in intermediately disturbed floodplains.

Keywords: semi-arid; wetlands; physical diversity; biodiversity; Murray Darling Basin; geochemistry

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1. Introduction

Disturbances are a component of every natural system [1–3] and can be broadly defined as "any relatively discrete event in time that disrupts ecosystem, community, or population structure and changes resources, substrate availability or the physical environment" [4]. On floodplains, disturbances can take a variety of forms. The most common, and the most important, is flooding, which can be both beneficial and harmful to floodplain environments. Positive benefits of flooding include a replenishment of soil nutrients and organic matter and the provision of water for plant and animal use (often resulting in breeding events and plant recruitment). Negative impacts of flooding (especially in larger floods) include soil erosion and the destruction of existing vegetation.

The research on disturbance over the past several decades has resulted in the development of the 'intermediate disturbance hypothesis' [1,4,5]. This hypothesis states that ecologic diversity will be highest at sites that have had an intermediate frequency of disturbance. An intermediate frequency of disturbance promotes diversity by: (1) preventing the competitive exclusion by the dominant species that can arise in infrequently disturbed sites; (2) facilitating greater diversity than that observed in highly disturbed sites where only species tolerant of the disturbance can thrive [1,6]. Support for the intermediate disturbance hypothesis has come primarily from studies of sessile organisms (i.e., organisms attached to a solid substrate). This is a consequence of the inability of these organisms to escape perturbation and because, in areas with intermediate disturbance regimes, sessile organisms often exhibit high levels of diversity [1,7]. The hypothesis has been supported by a series of empirical and theoretical studies, e.g., [1,6–8], most of which were conducted in high productivity areas, such as coral reefs and tropical forests. Studies on species with rapid growth rates, such as algae, have also tended to support the intermediate disturbance hypothesis [1,9,10].

The intermediate disturbance hypothesis has also been investigated in circumstances where flooding is the disturbance agent. This research has involved both sessile and mobile organisms including vertebrates and invertebrates [11]. Typically, the research into sessile organisms (either terrestrial or aquatic plants) tends to support the intermediate disturbance hypothesis, e.g., [7,12,13], with areas subject to frequent or high intensity floods displaying low levels of species diversity. These observations hold true irrespective of what type of flood environment is investigated (i.e., lake, river, or wetland) lending strong evidence to the notion that sessile organisms do respond to flood disturbances in a manner commensurate with the intermediate disturbance hypothesis. However, mixed results have been obtained in flood-disturbed environments when mobile organisms are considered. For example, the research by [14–16] using invertebrates, amphibians and nematodes as test organisms, respectively, supports the intermediate disturbance hypothesis in flood-disturbed sites. Meanwhile, studies conducted by [17,18] on macroinvertebrate communities in streams tend to refute the intermediate disturbance hypothesis with respect to flooding disturbance.

Similarly, the intermediate disturbance hypothesis has not been well supported in fire-prone communities [19,20], sediment-disturbed communities [21] or communities disturbed by human trampling [22], and several conflicting studies have reported that plant species richness can either increase [23–25] or decrease [23,26] along disturbance gradients. Perhaps because of these limitations, the use of the intermediate disturbance hypothesis as an explanatory theory in ecology has declined in recent years [27]. Despite this, the assumptions underpinning the hypothesis are interesting and may still be relevant for explaining diversity in many environments and as a consequence of many different types of disturbances, e.g., [9,28,29]. Interestingly, the intermediate disturbance hypothesis has only rarely been applied to physical systems. Given the strong links between physical habitat diversity and biological diversity [30–32], one might expect any increase in biological diversity to be mirrored by an increase in physical diversity. Indeed, it is not unreasonable to suggest that physical habitat diversity might both precede, and be instrumental to, the ecological diversity that occurs along disturbance gradients and that a lack of understanding of physical control may limit our ability to interpret biological distributions. To date, however, few studies have explicitly tested the intermediate disturbance hypothesis using physical variables.

The studies found in [33,34] explored links between flood patterns and heterogeneity in the functional traits of riparian plants in the Murray-Darling basin in south-eastern Australia (which includes the Murrumbidgee River). They found that certain plant functional traits, such as specific leaf area and seed mass, varied with hydrological conditions and that wood density was maximized at intermediate levels of hydrologic disturbance. Although directly relevant, Lawson et al. were unable to explain the causes for this relationship, proposing that ecological strategies might be driving the trend. However, it is possible that the ecological patterns are being reinforced by the spatial distribution of resources in the physical template of the landscape, but more research is required to ascertain this.

To address this limitation, this study uses soil character (i.e., the physical and chemical properties of the soil) along a flood frequency gradient to investigate the utility of the intermediate disturbance hypothesis as a theory to help explain physical diversity. Soils were collected along a flood frequency gradient from high disturbance frequency to no flooding disturbance to determine the diversity of soil character within high, low and intermediate flood disturbance categories. The results of this study can be used to assess the links between physical and biological diversity and to determine whether or not the intermediate disturbance hypothesis is a useful theory for explaining the diversity of physical systems.

2. Materials and Methods

2.1. Site Description

This research was undertaken in the Yanga National Park (hereafter referred to as Yanga NP) on the floodplain of the Lower Murrumbidgee River. The Lower Murrumbidgee (or Lowbidgee) floodplain is located within the semi-arid region of the Riverina Plains of south-eastern Australia (Figure 1a). It is considered one of the finest sheep-rearing areas in Australia and is fed by the lower reaches of the Murrumbidgee River near its confluence with the Murray River. The Lowbidgee floodplain is designated as an important Australian natural ecosystem (Environment Australia, 2001) and contains 217,000 ha of wetland, the largest area of floodplain wetland remaining in the Murrumbidgee Valley. It also holds one of the biggest River Red Gum (*Eucalyptus camaldulensis*) forests in Australia and large Lignum (*Muehlenbeckia florulenta*) wetlands [35]. As a consequence of the significance of this area, Yanga NP was acquired to preserve one of the most important, largely unaltered, wetland areas in south-eastern Australia. Yanga NP is situated near the western edge of the Murrumbidgee Catchment and is an elongated unit (spanning about 150 km of river frontage) that borders the south-eastern side of the Murrumbidgee River (Figure 1b) [36].

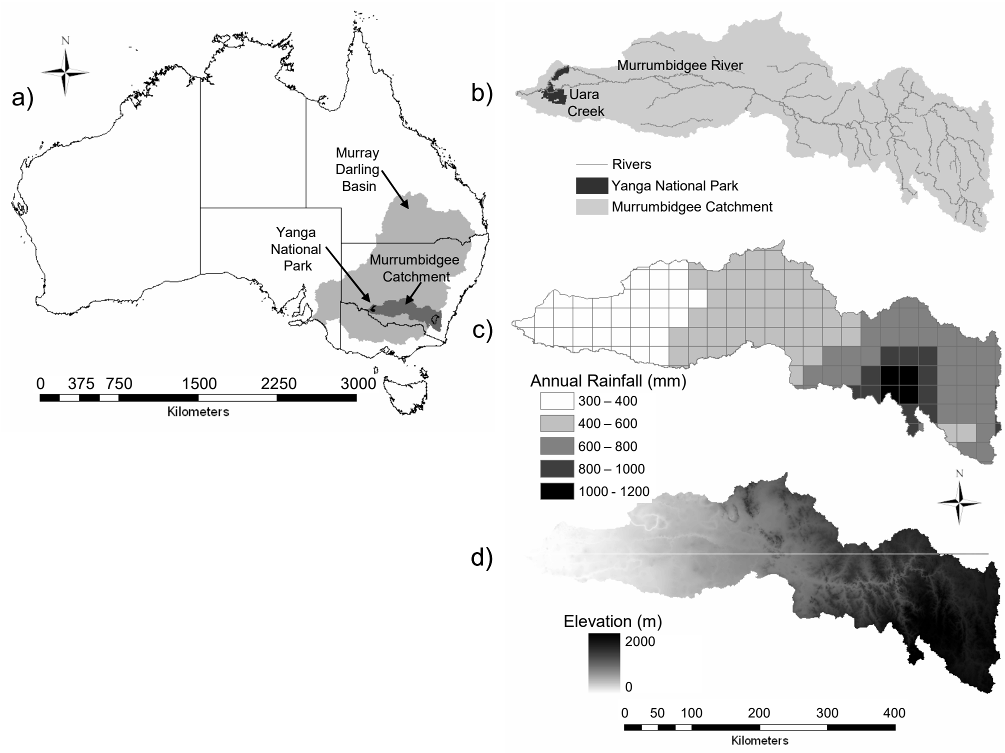

Figure 1. Murrumbidgee Catchment: (**a**) location; (**b**) stream network; (**c**) mean annual rainfall; (**d**) elevation.

A defining characteristic of the Lowbidgee region is the tendency for the Murrumbidgee River to become "choked" as it nears its junction with the Murray River [37,38]. This choking represents a natural progressive reduction in channel capacity that results from the avulsion of the original river channel. Prior to extensive catchment development, the choking created widespread flooding via a series of distributary creeks, the largest of which, Uara Creek, flows through Yanga NP (Figure 1b). Hence, it was possible for large floods to completely inundate the Lowbidgee region [39], thereby giving rise to its copious floodplain wetland environments. In recent years, however, water resource development has reduced the frequency of overbank flows and the complete inundation of the Lowbidgee is now relatively rare.

The Lowbidgee region is semi-arid with very low rainfall on the western side of the Murrumbidgee Catchment (Figure 1c). Consequently, flooding, from upstream rainfall on the eastern side of the catchment, is the principal driver of wetland and floodplain productivity in the Lowbidgee region. The Lowbidgee area is also very flat (Figure 1d) which contributes to the tendency for the river to anabranch, which in turn facilitates the widespread flooding that is characteristic of the region.

The Lowbidgee landscapes, including in the region of Yanga NP, are located within the Murray Geological Basin. This is a largely flat-lying basin whose uppermost sediments are dominated by late Cenozoic fluvial deposits known as the Shepparton Formation that extend to depths of approximately 50–70 m [40]. As a result, the soils of the Lowbidgee region are dominated by grey cracking and non-cracking clays formed from the repeated inundation of the landscape by prior streams over the Quaternary period. During dry events, these soils were reworked by aeolian processes that have produced sandy lunettes that are dotted across the landscape [40]. This has created a somewhat binary distribution of soils, with the flat floodplain surfaces being dominated by Vertisols (clays) and the lunettes being largely composed of sandy Rudosols.

In addition to supporting important ecological communities, the Murrumbidgee River provides water to a variety of land users. Indeed, it is classed as one of the most developed rivers in Australia, with floodplain inundation volumes estimated to be reduced by over 60% [41–43]. The extensive reduction in water availability throughout the system has had associated impacts on plant and animal distributions across the floodplain. However, the extent to which these changes may also be attributable to alterations in soil condition are not known. Thus, this study investigates how soil condition changes with flooding frequency on the lower Murrumbidgee River floodplain.

2.2. Data Collection

To investigate whether the intermediate disturbance hypothesis could apply to physical systems in the Lowbidgee floodplain, four flood frequency (or disturbance frequency) categories were derived. These are: a high-inundation-frequency flood zone (hereafter designated HF), which floods, on average, once per year; an intermediate-inundation-frequency zone (hereafter designated MF) which floods once in five years; a low-inundation-frequency zone (hereafter designated LF) which floods, on average, once in ten years; and a never flooded zone (hereafter designated NF) which is above the active floodplain and hence does not flood even during extreme events. In each flood frequency zone, three replicate sample locations were selected and within each of these a total of 10 soil samples were collected. Thus, 30 samples were taken from each of the 4 flood frequency zones giving a total of 120 samples. Each soil sample is a composite surface grab sample that was collected using a five-point-sampling technique (with sub-samples taken from the four corners and the center of a 2 m^2 plot).

The three sites in the high frequency flood zone (HF) were located in the north-west of Yanga NP (Figure 2). Two of the sites were positioned within Piggery Lake, one at the northern end and the other at the north-west side, and the third site was located further south within an area locally known as Breer Swamp. Red Gum trees (*Eucalyptus camaldulensis*) and Juncus (*Juncaceae* sp.), locally known as pipe grass, dominated the vegetation at these sites with Bluebush shrubs (*Maireana brevifolia*) also present at all sites although in fewer numbers (Figure 3a). The three replicates for the intermediate frequency flood zone (MF) were situated within the region known as Lower Fingerboard (Figure 2b). The sites were all positioned alongside Uara Creek. The low frequency sites (LF) were also located within Lower Fingerboard (Figure 2b) but were situated on higher elevation portions of the floodplain. Both the intermediate frequency (MF) and low frequency (LF) flooding zones were dominated by Spiny Salt Bush (*Rhagodia spinescens*), Old Man Salt Bush (*Atriplex nummularia*) and various species of the herbaceous flowering plant know as

Goosefoot (*Chenopodiaceae*) (Figure 3b,c, respectively). The HF, MF and LF sites were all located on Vertisol soil types.

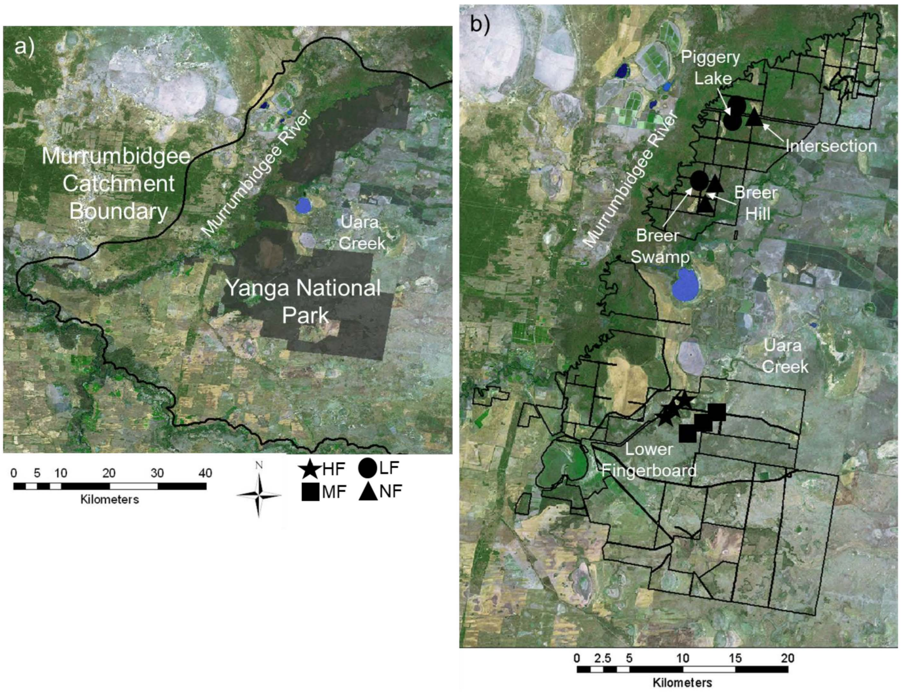

Figure 2. Aerial photographs illustrating the landscape surrounding Yanga NP: (**a**) location of the Murrumbidgee River and Uara Creek; (**b**) the sites selected for soil data collection. Note: HF = high frequency, IF = intermediate frequency, LF = low frequency, NF = never flooded.

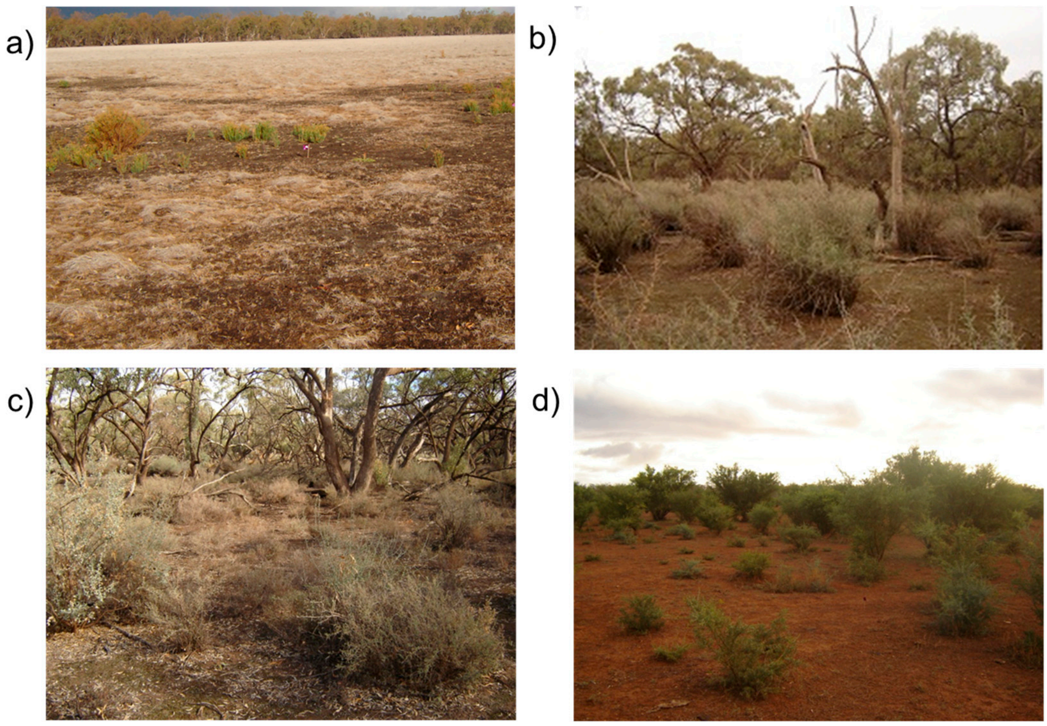

Figure 3. Examples of vegetation within the Yanga National Park flood frequency zones: (**a**) high frequency (HF); (**b**) intermediate frequency (IF); (**c**) low frequency (LF); (**d**) never flooded (NF).

The three hillslope (or never flooded) sites (NF) were located upon the sandy red hills found within Yanga NP (Figure 2). The first and second sites were located on Breer Hill while the final replicate was positioned at the intersection of Redbank, Top Narockwell and Tarwillie. The hillslope vegetation was dominated by patchy Goosefoot (*Chenopodiaceae*) mounds (Figure 3d). The NF sites were all located on Rudosol soil types.

Each soil sample was processed in a laboratory to derive a number of soil properties including: pH, electrical conductivity (EC), %organic matter, texture (%sand, %silt, %clay) and a suite of 26 geochemical variables (Al, As, Ba, Be, Ca, Cd, Co, Cr, Cu, Fe, K, Li, Mg, Mn, Na, Ni, P, Pb, S, Se, Si, Sn, Sr, Ti, V, Zn). The pH and EC were calculated following Australian Standards procedures (AS 1289.4.3.1 and AS 1289.4.4.1). The method used to assess soil geochemistry was based on the USEPA Method 3050B, which is designed to provide a rapid, multi-element, acid digestion of metals and metalloids and several other elements in the soil through inductively coupled plasma atomic emission spectrometry (ICPAES). The advantage of this method is that the results may be directly compared to both national and international databases and local guidelines. Particle size distributions were calculated using a soil hydrometer.

2.3. Data Analysis

Data distributions, means and coefficients of variation were determined for all soil variables and tests for normality were performed using XLStat. The majority of the parameters produced skewed distributions and thus, non-parametric analyses (Kruskal–Wallis and Mann–Whitney tests) were employed to determine whether there were statistically significant relationships between the soil parameters and the frequency of inundation. These two tests are robust, non-parametric procedures for determining whether two (Mann–Whitney) or three or more (Kruskal–Wallis) groups differ in their distributions. Kruskal–Wallis tests were initially undertaken to identify whether there was an overall difference in soil character as a function of inundation frequency. Mann–Whitney tests were then used to determine which inundation frequencies were significantly different to one another.

The soil character across the study area was further examined through a range of multivariate statistical analyses. A similarity matrix of Gower's similarity coefficients was first calculated using all soil variables and this matrix was used to test between disturbance frequency categories using the analysis of similarity (ANOSIM) routine in the PRIMER computer package. In addition, Semi-Strong-Hybrid Multidimensional Scaling (MDS) was used to represent the similarity matrix graphically. A stress level of less than 0.2 indicated that the ordination solution was not random. Finally, an agglomerative hierarchical clustering technique was applied to the multivariate data to elucidate whether or not the a priori groupings based on flood frequency were consistent with those groups that could be obtained objectively with no prior knowledge of soil sample locations. These data are also useful in demonstrating which soils are the most similar (or different) to each other and can therefore be used to help interpret soil differences along the flood frequency gradients.

3. Results

Summary statistics for each flood frequency category for the 33 soil properties included in this study are presented in Table 1 and the results of the Mann–Whitney U tests are presented in Table 2. Based on these results, it is evident that there are clear differences between the soil properties in each flood frequency category. The most pronounced differences occur between the areas that do flood (HF, MF, LF) and those that do not flood (NF). Of 33 variables in total, 29, 28 and 29 displayed significant differences between the NF and the HF, MF and LF zones, respectively. In addition, the HF zone was significantly different to the MF and LF zones in 22 and 18 out of 33 variables, respectively. Finally, significant differences between the MF and LF zones were found in 19 out of 33 variables. Thus, all of the flood frequency zones can be considered to have their own unique soil character.

Table 1. Summary statistics for each variable within the four flood frequency categories.

	HF		MF		LF		NF	
Variable	**Mean**	**CV**	**Mean**	**CV**	**Mean**	**CV**	**Mean**	**CV**
Al	32,543.7	0.07	26,576.2	0.16	34,960.5	0.28	17,174.1	0.28
As	2.7	0.08	2.7	0.22	3.9	0.27	2.2	0.33
Ba	127.7	0.13	107.7	0.14	101.7	0.11	100.9	0.14
Be	1.3	0.05	1.0	0.15	1.3	0.25	0.6	0.25
Ca	4118.8	0.23	3948.4	0.43	3854.2	0.40	11,509.4	1.26
Cd	0.09	1.33	0.09	0.27	0.09	0.33	0.13	0.24
Co	22.9	0.13	25.3	0.24	36.5	0.36	78.5	0.43
Cr	35.1	0.06	27.6	0.15	35.3	0.23	17.7	0.19
Cu	21.9	0.10	16.8	0.17	18.5	0.21	10.0	0.26
Fe	22,801.5	0.05	18,859.0	0.17	26,190.6	0.26	13,039.0	0.24
K	5317.2	0.08	6684.1	0.24	7869.9	0.21	5179.3	0.30
Li	15.6	0.08	14.2	0.16	19.2	0.29	8.6	0.27
Mg	3992.1	0.06	3673.3	0.23	5094.2	0.24	2930.7	0.37
Mn	218.8	0.24	190.5	0.35	397.5	0.16	218.3	0.25
Na	343.0	0.31	277.1	0.48	674.2	0.45	433.9	1.15
Ni	22.0	0.06	17.5	0.16	21.3	0.24	10.2	0.26
P	429.6	0.36	366.3	0.35	445.8	0.18	320.6	0.45
Pb	15.6	0.98	11.2	0.12	12.5	0.16	6.8	0.96
S	647.0	0.40	382.0	0.64	271.6	0.48	195.4	0.48
Se	1.4	0.17	1.7	0.21	2.1	0.18	4.9	0.32
Si	1361.7	0.61	2299.1	0.21	1296.5	0.58	2159.0	0.10
Sn	1.2	1.72	0.9	1.13	0.5	0.33	2.0	4.79
Sr	35.2	0.18	37.0	0.34	39.1	0.23	57.9	1.17
Ti	88.7	0.41	165.7	0.11	179.6	0.22	94.0	0.19
V	44.4	0.06	35.8	0.22	48.0	0.29	24.8	0.26
Zn	57.8	0.33	42.5	0.15	49.8	0.17	25.4	0.26
EC	425.7	0.73	397.1	0.94	410.3	0.76	315.1	0.81
pH	6.0	0.13	6.4	0.13	6.7	0.10	6.9	0.13
%OM	12.9	0.40	9.7	0.50	9.2	0.47	4.5	0.53
%Clay	9.1	0.14	8.6	0.18	14.6	0.46	5.4	0.41
%Silt	70.1	0.12	59.3	0.11	61.2	0.11	27.9	0.24
%Sand	20.8	0.39	32.1	0.22	24.2	0.52	66.7	0.13
Soil Texture	Silt loam		Silt loam		Silt loam		Sandy loam	

Note: HF = high frequency; MF = intermediate frequency; LF = low frequency; and NF = never flooded. Units for geochemical variables are ppm and for EC are µS/cm.

The next step in the analysis was to determine whether or not the variability of soil character within each flood zone was similar as this is an indicator of soil diversity. A series of F tests was performed for this purpose, which showed that there were many significant differences between the variability of soil properties among flood frequency categories (Table 3). This indicates that there may be some association between the frequency of disturbance and the diversity of soil character within Yanga NP. To determine which flood frequency zones had the most diverse soil properties for each of the 33 variables included in this study, the F test results can be compared to the summary statistics presented in Table 1. When the HF zone is compared to the two intermediate flooding zones (MF and LF), only eight soil components (Cd, P, Pb, Si, Sn, Ti and Zn) have higher variabilities in the HF zone while for twenty-two out of thirty-three soil components the MF and/or LF zone have higher variabilities than those in the HF zone. The NF zone, however, has 16 soil components (As, Ca, Co, Cu, K, Mg, Na, Ni, P, Pb, Se, Sn, Sr, Zn, %OM, and %silt) with higher variabilities than those found in the intermediate flood zones (MF and LF).

Table 2. *p* values for Mann–Whitney tests to determine whether data from each flood frequency category could be considered to originate from the same population.

Variable	HF v MF	HF v LF	HF v NF	MF v LF	MF v NF	LF v NF
Al	0.000	0.906	0.000	0.000	0.000	0.000
As	0.231	0.000	0.000	0.000	0.003	0.000
Ba	0.000	0.000	0.000	0.198	0.071	0.647
Be	0.000	0.261	0.000	0.001	0.000	0.000
Ca	0.110	0.107	0.000	0.894	0.000	0.000
Co	0.425	0.000	0.000	0.000	0.000	0.000
Cd	0.055	0.200	0.000	0.936	0.000	0.000
Cr	0.000	0.690	0.000	0.000	0.000	0.000
Cu	0.000	0.002	0.000	0.104	0.000	0.000
Fe	0.000	0.249	0.000	0.000	0.000	0.000
K	0.000	0.000	0.779	0.005	0.002	0.000
Li	0.008	0.031	0.000	0.000	0.000	0.000
Mg	0.084	0.000	0.000	0.000	0.007	0.000
Mn	0.017	0.000	0.894	0.000	0.049	0.000
Na	0.003	0.000	0.043	0.000	0.301	0.000
Ni	0.000	0.214	0.000	0.005	0.000	0.000
P	0.074	0.231	0.005	0.008	0.121	0.000
Pb	0.000	0.615	0.000	0.007	0.000	0.000
S	0.000	0.000	0.000	0.139	0.001	0.023
Se	0.001	0.000	0.000	0.001	0.000	0.000
Si	0.000	0.756	0.001	0.000	0.003	0.000
Sn	0.049	0.000	0.000	0.139	0.000	0.000
Sr	0.848	0.092	0.027	0.294	0.029	0.027
Ti	0.000	0.000	0.048	0.098	0.000	0.000
V	0.000	0.688	0.000	0.000	0.000	0.000
Zn	0.000	0.012	0.000	0.002	0.000	0.000
pH	0.026	0.001	0.000	0.200	0.011	0.108
EC	0.341	0.341	0.341	0.536	0.759	0.341
%OM	0.011	0.002	0.000	0.536	0.000	0.000
%Sand	0.000	0.026	0.000	0.026	0.000	0.000
%Silt	0.000	0.000	0.000	0.200	0.000	0.000
%Clay	0.200	0.000	0.000	0.000	0.000	0.000

Note: HF = high frequency; MF = intermediate frequency; LF = low frequency; and NF = never flooded. Cells containing *p* values below 0.05 are statistically significant and shaded grey.

Table 3. *p* values of F tests to determine significant differences in the variability of soil properties among each flood frequency category.

Variable	HF v MF	HF v LF	HF v NF	MF v LF	MF v NF	LF v NF
Al	<0.0001	<0.0008	<0.0001	<0.0001	<0.0004	0.4192
As	<0.0001	<0.0001	<0.0001	0.0038	0.0470	0.3396
Ba	0.0300	0.8232	0.4212	0.0506	0.1657	0.5607
Be	<0.0001	<0.0001	<0.0001	0.0004	<0.0001	0.6736
Ca	0.0104	0.0027	<0.0001	0.6387	<0.0001	<0.0001
Cd	<0.0001	<0.0001	<0.0001	0.3264	0.7518	0.1956
Co	<0.0001	0.0002	<0.0001	<0.0001	<0.0001	<0.0001
Cr	<0.0001	0.0007	0.0128	0.0003	<0.0001	0.3432
Cu	0.0072	0.2927	0.5179	0.0942	0.0385	0.6831

Table 3. *Cont.*

Variable	HF v MF	HF v LF	HF v NF	MF v LF	MF v NF	LF v NF
Fe	<0.0001	<0.0001	<0.0001	0.0002	<0.0001	0.8734
K	<0.0001	<0.0001	<0.0001	0.9115	0.7834	0.8699
Li	<0.0001	0.0007	0.0006	<0.0001	<0.0001	0.9612
Mg	<0.0001	<0.0001	<0.0001	0.0482	0.5994	0.1434
Mn	0.3279	0.2052	0.8218	0.7705	0.4505	0.2963
Na	<0.0001	0.2089	<0.0001	<0.0001	0.0083	<0.0001
Ni	<0.0001	0.0002	0.0008	0.0027	0.0008	0.6946
P	0.0010	0.2918	0.7261	0.0215	0.0030	0.4801
Pb	<0.0001	<0.0001	<0.0001	0.0430	<0.0001	<0.0001
S	0.0004	0.7409	<0.0001	0.0011	0.0892	<0.0001
Se	0.0168	0.0223	<0.0001	0.9119	<0.0001	<0.0001
Si	0.5524	0.0053	<0.0001	0.0262	<0.0001	<0.0001
Sn	<0.0001	0.0002	<0.0001	<0.0001	<0.0001	<0.0001
Sr	0.0588	0.0003	<0.0001	0.0671	<0.0001	<0.0001
Ti	0.7375	0.0002	0.0002	<0.0001	<0.0001	0.9839
V	<0.0001	<0.0001	<0.0001	0.0032	<0.0001	0.2814
Zn	<0.0001	<0.0001	<0.0001	0.1792	0.1627	0.9572
pH	0.5278	0.6917	0.3665	0.3050	0.1268	0.6114
EC	0.9540	0.3190	0.3003	0.3476	0.2744	0.0439
%OM	0.3688	0.8022	<0.0001	0.5160	0.0023	0.0003
%Sand	0.0253	0.4082	0.7362	0.0025	0.0558	0.2456
%Silt	0.3277	0.1760	0.3076	0.7049	0.9665	0.7363
%Clay	<0.0001	0.3473	0.0055	<0.0001	<0.0001	0.0606

Note: HF = high frequency; MF = intermediate frequency; LF = low frequency; and NF = never flooded. Cells containing p values below 0.05 are statistically significant and shaded grey.

Any soil is comprised of a number of properties, each of which may behave quite independently to other soil components. Therefore, it was necessary to adopt a multivariate approach to determine whether or not the soils as a whole could be considered to be both different and more variable in intermediately disturbed locations. To this end, all 33 variables were included in a multivariate analysis to determine the diversity of the soils themselves, not just their individual properties.

First, an agglomerative hierarchical clustering technique was employed to determine how the sites within flood frequency categories related to one another from a multivariate perspective (Figure 4). Figure 4 clearly shows that the greatest differences within the soils of Yanga NP occur between zones that flood and those that do not with the NF zone separating out from all other zones at a dissimilarity value of approximately 68%. The next zone to separate out was the LF zone which separated from the HF zone at dissimilarity values of 54% for 11 sites and 32% for the remaining 19 sites. The 19 LF sites that separated out at the 32% dissimilarity level from the HF sites were similar to 20 of the MF sites indicating that the LF and MF zones have considerable overlap. The remaining nine MF sites grouped with the HF sites again at the 32% dissimilarity level.

To determine whether or not there were significant differences between the soils in each flood frequency category, a multidimensional scaling (MDS) plot was produced (Figure 5) and an Anosim was performed (Table 4). Results from both analyses confirm that there are statistically significant differences between the soils in each flood frequency category with the NF soils being the most distinct. There are also clear differences between the HF zone and the MF and LF zones but considerable overlap between the MF and LF zones. Thus, the MF zone and the LF zone are most similar from a multivariate perspective although they are still significantly different. Finally, a multivariate dispersion index was computed which determines the variability of the soil properties within each flood frequency category

(Table 4). The results of this analysis show that the MF and LF zones have significantly higher multivariate dispersion values than the HF zone indicating that these soils are more diverse from a multivariate perspective. However, the dispersion value for the NF zone fell between those of the MF and LF zones indicating that its variability is not lower than those of the intermediately disturbed zones.

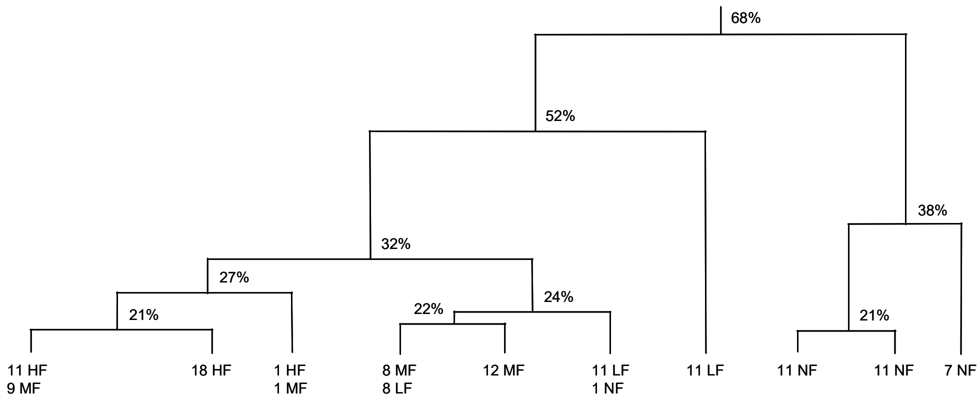

Figure 4. Agglomerative hierarchical cluster diagram illustrating the dissimilarity between soils in each flood frequency category. Percentage values indicate the percent dissimilarity between sites at each break in category membership. Numbers along the bottom of the plot indicate the number of sites within each flood frequency category that fall within each group. HF = high frequency; MF = intermediate frequency; LF = low frequency; and NF = never flooded.

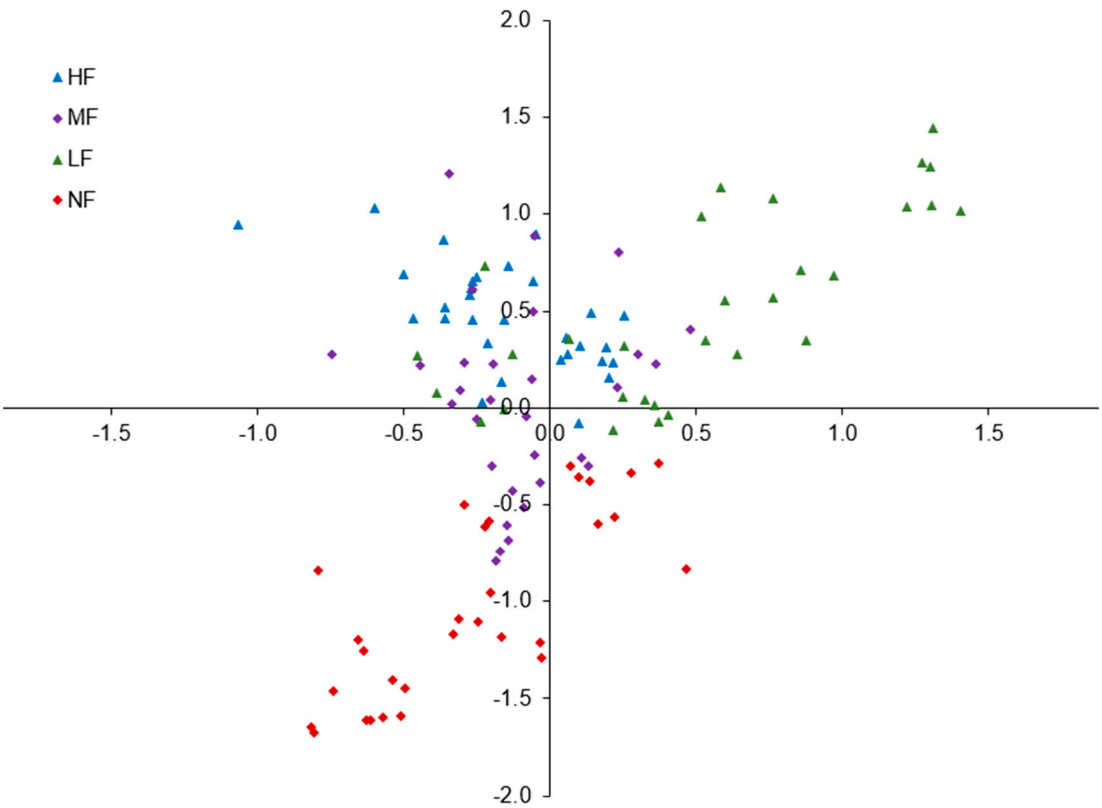

Figure 5. Multidimensional scaling plot illustrating the uniqueness and variability of each flood frequency category in multivariate space. Note: HF = high frequency; MF = intermediate frequency; LF = low frequency; and NF = never flooded.

Table 4. Anosim and multivariate dispersion results comparing flood frequency categories based on the 32 soil variables assessed in this study.

Flood Frequency	Anosim HF	MF	LF	NF	Multivariate Dispersion
HF					0.740
MF	0.581				0.915
LF	0.552	**0.323**			1.258
NF	**0.947**	0.694	**0.768**		1.094

Note: HF = high frequency; MF = intermediate frequency; LF = low frequency; and NF = never flooded. **Red** font indicates clear separation between categories; **grey** font indicates some overlap between categories; **black** font indicates considerable overlap between categories.

4. Discussion

This study compares soils collected from sites in a semi-arid wetland subject to differing frequencies of flood disturbance. Disturbance by flooding was used in this study because it is understood to be a relatively common disturbance type in semi-arid floodplain–wetland systems and is responsible for driving ecological functioning in this environment [44–47]. The results of this study indicate that the occurrence of flooding leads to a clear difference in soil character when compared to sites that do not experience disturbance by flooding (i.e., hillslope (NF) areas above the 100 yr. floodplain). Indeed, when the NF zone was compared to the three zones that experience flooding (i.e., HF, MF and LF), nearly all 33 of the soil properties investigated in this study displayed both significantly different mean properties and variabilities. From a multivariate perspective, the NF zone also displayed a clear dissimilarity to the flood susceptible zones with a dissimilarity of 68% separating it from the HF, MF and LF zones.

Each of the flood susceptible zones also displayed its own unique soil character. Thus, the HF, MF and LF zones are all distinct from one another. Of these, the HF zone has the most singular soil character although it has some overlap with the MF zone (see Figure 4). The MF and LF zones, although statistically different both from univariate and multivariate statistical perspectives, also share some commonalities as evidenced by the relatively low R value (0.323) obtained by the Anosim for these two zones.

A more detailed look at the soil properties within each flood frequency zone shows that the NF zone has lower levels of Al, As, Be, Cr, Cu, Fe, K, Li, Mg, Ni, P, Pb, S, V, EC, %OM, Clay and Silt and higher levels of Ca, Cd, Co, Se, Sn, Sr and sand than the zones that flood (the HF, MF and LF zones). Hence, the flooded zones can be considered to be zones of enrichment in terms of geochemistry and organic matter relative to the NF zone. Indeed, the only important plant nutrient with higher levels in the NF zone than the flood zones was Ca and the relatively high sand content in the NF zone means these soils will be less able to store soil moisture for use by plants. In terms of the three flood-prone zones, the HF zone had a distinctly lower Ti content than the MF and LF zones and the MF zone had lower levels of Al, Cr, Fe, Ni, P and V than the HF and LF zones. Meanwhile, the HF zone also had higher levels of Ba, Cu, Pb, S, Sn, Zn, %OM and silt than the MF and LF zones, the MF zone was enriched in Si and sand relative to the HF and LF zones and the LF zone had the highest levels of As, Co, K, Li, Mg, Mn, Na and clay of any flood-prone zone. These results contribute to our understanding of the importance of overbank flows for improving soil enrichment on semi-arid floodplains and point to the importance of maintaining connections between these landscapes and their critical water sources [48–51].

To address the principal question of the suitability of the intermediate disturbance hypothesis for explaining the diversity of physical systems it is necessary to look more closely at the variability in soil character within each flood disturbance zone. The intermediate disturbance hypothesis posits that species diversity is maximized at intermediate levels of physical diversity [52,53]. If this hypothesis is to be validated in these systems, the variability in soil character should be greater in the intermediately disturbed flood zones (i.e., the MF or LF zones) relative to that in zones highly disturbed (HF) or never disturbed (NF) by floods. This would indicate a greater diversity of soil character in the intermediately disturbed zones, which would equate to the higher biological diversities previously attributed to intermediate levels of disturbance [1,7,10] in other environments.

A consideration of the variability in soil character between those zones susceptible to flooding (i.e., the HF, MF and LF zones) shows that zones subject to intermediate levels of flood disturbance (i.e., the MF and LF zones) display greater diversity than sites subject to frequent disturbances (i.e., the HF zone). Indeed, two-thirds of the individual soil properties investigated here displayed greater variability in the intermediately disturbed zones when compared to the frequently disturbed zones. These results are supported by the multivariate dispersion index (a multivariate measure of variability) which shows that both the LF and MF zones are significantly more variable than the HF zone with the highest variability found in the LF zone. These results show that the LF zone should be considered the intermediately disturbed zone, as soil heterogeneity continues to develop between the five-year recurrence interval of the MF zone and the ten-year recurrence interval of the LF zone. Meanwhile, heterogeneity declines between the 10-year recurrence interval of the LF zone and the never-flood-disturbed NF zone. Hence, the results obtained for the sites subject to flooding disturbance tend to support the intermediate disturbance hypothesis and suggest that this theory may be applicable to physical systems.

The present study may help explain the patterns observed in the work by, for example, [33,34] in that it is likely that the plant responses they found were related to changes in physical habitat characteristics driven by the flood frequency differences between their sites. The potential for close associations between physical template heterogeneity (be it soil character, as in the case of this study, geomorphic features or other physical characteristics) offers a possible explanation as to why the intermediate disturbance hypothesis has lost some favor amongst ecologists as an explanatory theory [27,54]. This study shows that heterogeneity in the physical template on which biota depend (i.e., the soil) seems to be maximized at intermediate levels of disturbance. This suggests that ecological applications of the intermediate disturbance hypothesis may require a more holistic view of disturbance theory that includes a joint consideration of both physical template heterogeneity and biological diversity. Such a focus could reinvigorate research on the importance of intermediate disturbance in ecological systems, which is particularly relevant as climate change threatens to impact on the frequency and intensity of physical disturbances.

Although the findings of this study support a link between soil heterogeneity and flood disturbance, the lack of systematic flood-frequency mapping in Yanga NP limits the capacity to identify flood frequencies rarer than 1-in-10 years. As such, rare flood sites (e.g., those with flood recurrence intervals of 50 or 100 years) could not be identified for this study. To compensate for this, never flooded sites were used as the end member of the flood disturbance spectrum. This was a valid approach but it limits the capacity of this study to identify the point at which soil heterogeneity is actually maximized in association with declining flood frequency. Thus, the findings of this study provide an indication of the validity of employing a physical corollary of the intermediate disturbance hypothesis to explain soil heterogeneity in this region, but more work is required to define this.

Given that the evidence on the other end of the spectrum (i.e., intermediately to frequently disturbed sites) showed very convincingly that decreasing levels of flood disturbance favor soil diversity, this study suggests that the intermediate disturbance hypothesis does in fact apply to physical systems. However, additional evidence is needed to validate this conclusion, ideally from a site with a better defined flood frequency regime from which a wider range of flood frequency zones could be sampled. Ideally, these would range from 1 to 2 year flood recurrence intervals up to 100 year or greater flood recurrence intervals with a range of intermediate flood recurrence levels included as well. Not only would this provide additional evidence as to whether the intermediate disturbance hypothesis is applicable to physical systems, it would also help to identify what exactly constitutes an intermediate level of flood disturbance (e.g., 5 years, 10 years, 20 years, etc.) in a semi-arid environment. This work could be performed in tandem with a biological investigation looking at the diversity of the vegetation within these flooded areas to further elucidate the links between the intermediate disturbance hypothesis as it applies to both physical and biological systems.

5. Conclusions

This study set out to determine whether the intermediate disturbance hypothesis, previously reserved to biological systems, is also a valid theory for describing diversity in physical systems. To address this, soil character was assessed at a series of floodplain sites that experienced varying frequencies of flooding disturbance. Sites subject to an intermediate level of flood disturbance did show a greater level of diversity in soil properties than those in sites subject to frequent flood disturbances. Hence, the results of this study suggest that the intermediate disturbance hypothesis can be applied to physical systems, at least where the disturbance mechanism is consistent between sites. The greater diversity in soil character observed in the intermediately flood disturbed sites in Yanga NP may be one of the conditions that favors the higher plant diversity found in these same sites. Hence, our existing understanding of what generates biodiversity in intermediately disturbed sites, which can be summarized in purely ecological terms as the prevention of competitive exclusion by dominant species (in sites not disturbed by flooding) and the importance of disturbance tolerance as a diversity-limiting factor (in highly disturbed sites), may need to be expanded to recognize a more diverse physical template being present in intermediately disturbed sites and creating a wider range of habitat types than that available in sites that are frequently or not disturbed by floods.

Additional research on the links between physical diversity and disturbance frequencies for different types of disturbances and different physical characteristics needs to be undertaken to verify the results obtained in this study. In addition, a more complete investigation into the relationship between the frequency of flood disturbance and soil character is also needed, especially with respect to the inclusion of a wider range of flood disturbance frequencies. However, the results of this study are very promising and represent evidence of a link between disturbance frequency and physical diversity. If this relationship is verified by additional research, it will provide an important contribution to our understanding of the links between physical and biological systems and will justify the approach of adopting an interdisciplinary approach (especially around theory development) when investigating biophysical systems.

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