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# Assessment of riparian vegetation characteristics in Mediterranean headwaters regulated by check dams using multivariate statistical techniques

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## ABSTRACT

In mountainous torrents of the Mediterranean environment the riparian vegetation is strongly influenced by the presence of engineering control works, since these structures bring heavy modifications in channel geometry, hydraulic regime and bed sediment size. Previous investigations have shown high linear correlations between physical (section shape, profile slope, specific discharge, surface and subsurface size of the channel bed) and vegetation (development, structure and biodiversity) indicators in headwater channels with check dams of Calabrian (Southern Italy) torrents. Based on these findings, this study applies multivariate statistical techniques (Principal Component Analysis and Partial Least Square Regression) to identify in the same study headwaters new synthetic explanatory variables, representative of the different transects (upstream, downstream or intermediate, compared to the check dam location) and develop predictive models of riparian vegetation characteristics.

The Principal Component Analysis has provided a simple parameter (the first Principal Component, explaining about 60% of the total variance), which is able to discriminate the physical and vegetal characteristics of the different transects close to check dams, thus reducing the large number of factors influencing the fluvial processes. Moreover, cover, height and transversal variability of riparian vegetation have a very high influence (loadings over 0.73) on this component, while its biodiversity is correlated to the second Principal Component (loadings over 0.63). The Partial Least Square Regression has shown that it is possible to estimate with fair accuracy (minimum $r^2$ of 0.70) the development, structure as well as transversal variability of the riparian vegetation, starting from the physical features of the channel. These models may be important in the planning steps of new check dams, since their effects on the development and growth of vegetation upstream and downstream can be forecasted before their installation, at least for the quantification of the order of magnitude of the check dam impacts on torrent ecology.

**KEYWORDS:** channel morphology; river hydraulics; bed sediment; vegetation biodiversity; principal component analysis; partial least square regression.

## 1. INTRODUCTION

The torrents of the Mediterranean environment are subject to high magnitude flash floods with high erosive power, often causing hydro-geological instability and disruption (Fortugno et al., 2017) in response to specific local conditions (e.g. frequent and intense rainstorms, small drainage basins, steep slopes, Zema et al., 2014). In many of these contexts (such as in Southern Italy and Spain, as reported, for instance, by Bombino et al., 2007, and Boix-Fayos et al., 2007), local administrations have funded public works from 60-70 years, in order to control and mitigate the hydro-geological risk. Reforestation and check dams installation were chosen as techniques for controlling erosion and sediment circulation along a watershed (Ramos-Diez et al., 2016a).

However, whereas reforestation is considered as an eco-compatible measure, the use of engineering control works, such as the check dams, is usually thought to be a mitigation strategy with a high impact on torrent ecosystem, especially in very delicate river environmental contexts, such as the headwaters (Marmontel et al., 2018). In fact, in mountain streams, where the human impact is low, the installation of check dams modifies the natural evolutionary processes and may have noticeable influences on torrent geomorphology, hydrology and ecology (Zema et al., 2018). Moreover, the lack of reliable criteria for assessing the impact of engineering works on riparian vegetation has often yielded difficulties and uncertainties in the approval process for torrent control works (Bombino et al., 2006), increasing the reluctance of the riverine authorities and communities towards check dam installation to regulate rivers. This is also due to the lack or to the insufficient knowledge of the effects of engineering works on river ecology and especially on development and biodiversity of riparian vegetation in torrents regulated by check dams.

Eminent and ample literature exists, which has widely debated the effects of engineering works (large dams, embankments and check dams) on riparian vegetation characteristics, although quantitative evaluations of the impact of control works on riparian vegetation are rather limited (Bombino et al., 2006). For instance, Gurnell (1995) and Hupp and Rinaldi (2007) have shown that particular vegetation species and communities are associated with specific fluvial landforms in many environments; these associations and interactions between fluvial processes and forms and ecological processes of mountainous streams can be strongly impacted by engineering control works (e.g., Nakamura et al., 2000; Petts and Gurnell, 2005; Bombino et al., 2007; Zema et al., 2018). Literature has also demonstrated the complexity of the check dam actions on torrent hydrology (e.g. Norman et al., 2016; Guyassa et al., 2017), morphology (e.g. Boix-Fayos et al., 2007; Gao et al., 2016; Fortugno et al., 2017) and sedimentary effects (e.g. Ramos-Diez et al., 2016a; 2016b; 2017a; 2017b).

The reciprocal interactions among the factors influencing channel geometry, bed sediment size and riparian vegetation were recently studied by Zema et al. (2018) in Mediterranean mountain torrents. Beside the complexity of these factors, this investigation has also shown that high linear correlations exist, regressing cover, structure and transverse variability of riparian vegetation on morphological, hydraulic and sedimentary characteristics of channel with check dams. These quantitative relationships let us suspect that, in headwaters of semi-arid torrents, it is possible to predict the characteristics of the riparian vegetation close to check dams and separately for upstream and downstream sites; in our hypothesis, this goal may be achieved by applying multivariate statistical techniques to a set of indicators of physical local characteristics of the active channels. This hypothesis has been tested in headwaters of four torrents in Calabria (Southern Italy), where (i) new synthetic explanatory variables, representative of the different transects (upstream, downstream or intermediate compared to the check dam location), are derived from the physical indicators, using the Principal Component Analysis; (ii) predictive models of riparian vegetation characteristics are developed using the Partial Least Square Regression. If such models have a sufficient prediction capability, a useful tool to provide the characteristics of riparian vegetation from the physical properties of headwaters before check dam installation in the Mediterranean torrent ecosystem. The proposed models integrate the quantitative relationships previously established between the physical adjustments close to check dams (e.g., channel geometry and profile slope, bed sediment size, flow regime) and some biological processes acting in the torrents (e.g., development, growth and distribution of riparian vegetation and its biodiversity). This allows the prediction of the characteristics of the riparian vegetation assuming physical indicators - relatively easy to survey - as input parameters. At the authors' knowledge no evidence of similar prediction models exists in literature.

## 2. MATERIALS AND METHODS

### 2.1. Study torrents

The torrents of Calabria (Southern Italy) - the so-called "fiumaras" - are peculiar water courses, characterised by small drainage basins and channels with steep longitudinal profiles (Bombino et al., 2009). Four torrents were selected as case studies, all sourcing in the Aspromonte mountain chain (over 1200 m above sea level); two torrents drain towards the south east and discharge into the Ionian sea (Allaro, hereinafter “A”, and Torbido di Gioiosa, “TG”), and two (Sant’Agata, “SA”, and Gallico, “G”) flow towards the south west and their mouths lays over the Tyrrhenian coast (Figure 1). Their area ranges from 55 ("G") to 160 ("TG") km$^2$, while the length of the main stream is 5.5 ("A") to 7.2 ("G") km. The four torrents are regulated by 44 ("A") to 196 ("TG") check dams, located into the whole watersheds.

For this investigation the mountain reaches (headwaters) of fiumaras were focused (Figure 1), since in these river channels riparian vegetation naturally develops, the installation of check dams being the only human disturbance factor. The analysed headwaters were identified after a prior subdivision of the river environment in torrent reaches with homogeneous conditions in term of vegetation characteristics, climatic and geomorphological factors (according to Bombino et al., 2006; 2007).

Table 1 reports the main headwater characteristics of the four analysed headwaters. As regards the climate - hot-summer Mediterranean (Csa, according to the Köppen climate classification, Kottek et al., 2006), - and hydrological regime, the headwaters are located in the same pluviometric region (Versace et al., 1989) and the contributing areas show similar size and times of concentration (Table 1). In the headwaters winters become very cold and summers are cool, with a total annual precipitation between 1351 (SA) to 1780 (A) and mean annual temperatures between 9.9 (G) and 11.2 (A) °C.

The flow regime is controlled by sudden storms and, once every almost two or three years, by episodic and intense flash floods, which are generally responsible for cross-section modelling (Zema et al., 2018) with no heavy geomorphic adjustments on bed longitudinal profile (Fortugno et al., 2017). However, extreme events (such as heavy flash floods with high recurrence times) thoroughly remodel the torrent morphology by transporting along the profile the sediment eroded on hillslopes and delivered to the channel.

The mountain reaches of the four studied torrents are characterised by: (i) catchment areas between 10 (TG) and 48 (A) km$^2$; (ii) main channels from 3.7-km (TG) to 7.0-km (SA) long; (iii) narrow sections from 10.5-m (TG) to 34-m (G) wide; (iv) thalwegs with a mean longitudinal slope from 9.2% (A) to 11.4% (SA) (with sub-reaches getting 20%).

According to the CLC classification (2016), the land use of the four mountain reaches is predominantly forest (mainly *Fagus sylvatica L.*, *Pinus nigra ssp. Laricio var. calabrica* and *Abies alba Mill.*) and shrub, which cover from 77% (SA) to 93% (G) of the headwater area. Other land uses in the headwaters are intensive crops (on average 20% in the four basins area) and complex crop system (on average about 5%). Soils are mainly Humic Dystrudept in SA and G headwaters (56% and 47% of the area, respectively), Humic Lithic Dystruxerodept in TG (44%), and Dystrudepts in A (39%), according to the USDA Soil Taxonomy classification, 1999). Other soils of the four headwaters are Typic Dystrudepts and Humic Dystruxerodept (Table 1).

As happened in the majority of the fiumaras of Calabria and Sicily (Southern Italy), public works including reforestation of large areas and construction of series of check dams in the channels were carried out at the middle of the twentieth century. The goal of the check dam construction strategy was primarily the stabilisation of the longitudinal bed profile by graded sub-reaches (with a longitudinal slope lower than the original profile) and secondarily consolidating torrent banks from lateral erosion (Fortugno et al., 2017). At a later date (predominantly the 1970s), additional smaller check dams (about 3-m high) were built to prevent local scouring downstream of the existing check dams. Currently, the main channel of the studied headwater shows the presence of about 10 to 50 staggered check dams (from 2.5-m to 10-m high), made of concrete or stone and concrete. Almost all structures are completely filled up with sediments and thus and their sediment storage capacity is now depleted (Zema et al., 2014).

## 2.2. Methodology

Part of the methods adopted in this investigation (namely the identification of check dams and survey transects, the selection of the physical and vegetation indicators and the survey and analysis methods) is common to the parent study of Zema et al. (2018). Referring to this study for more detailed information, here the main steps are summarised.

### *2.2.1 Identification of check dams and survey transects*

In each headwater of the four study torrents, five reaches (each one containing a check dam) were identified and studied. In every reach three transects were located, of which two positioned in proximity to a check dam (one upstream and one downstream) and the third one positioned in an intermediate zone between two check dams. Therefore, 60 sampling locations (3 transects x 5 reaches x 4 headwaters) were considered. Upstream (henceforth indicated by the letter “U”) and downstream (henceforth “D”) transects represent torrent zones under the direct influence of the check dams, while the intermediate transects (henceforth "I") are sites less disturbed by the presence of the structures and thus were assumed as control (Bombino et al., 2006).

### *2.2.2 The physical and vegetation indicators adopted*

As physical characteristics, channel morphology, hydraulic regime of the water stream and bed (surface and sub-surface) sediment parameters were considered; as vegetation characteristics, development (that is, extension, structure and spatial distribution) and biodiversity (that is, species richness, relative abundance and degree of integrity) of the riparian vegetation were focused. In order to give a quantitative approach to our study, these physical and vegetation characteristics were studied through as many synthetic but representative parameters (henceforth indicated, in general terms, as "indicators"), calculated based on field surveys and measurements. Table 2 reports the physical and vegetation indicators adopted, together with their survey/calculation methods.

The physical indicators adopted are summarised as follows (Table 2):

- for morphology of the active channel, the “width to depth ratio” (w/d, [m $m^{-1}$]) of the transect cross section and the local slope (LS, [%]) of the longitudinal profile of the thalweg;
- for torrent hydraulic regime, the discharge (q) per unit width required to fill the active channel (henceforth called "specific discharge");
- for the characteristics of the torrent bed material, the median particle size of surface sediments ($SD_{50}$, [mm]) and the percentage of subsurface finer sediments (SSF, [%]).

As regards the characteristics of the riparian vegetation, the following indicators were chosen (Table 2):

- the Global Canopy Cover (GCC, [%]), sum of the percent cover of the herbaceous, shrub and tree layers multiplied, respectively, by 1/6, 2/6 and 3/6, in order to take into account the ecological importance of each layer;
- the Weighted Canopy Height (WCH, [m]), sum of the products of the average height of the individual layers (herbaceous, shrub, tree) and the corresponding canopy cover;
- the Coefficients of Variation of $CV_{GCC}$ ([%]) and $CV_{WCH}$ ([%]), which measure the transverse variability of extension and structure of the riparian vegetation.

The biodiversity of riparian vegetation was quantified by the following indicators (Table 2):

- the α-diversity index ($H_\alpha$), proposed by Hill (1973) for the species richness (for $\alpha = 0$) and the relative abundance (for $\alpha = 2$);
- the ratio ($Ns_A/Ns_N$) between the number of alien (henceforth “A”) and native (“N”) species in each transect, which measures the degree of integrity of vegetation.

### *2.2.3. Survey and analysis methods*

In order to calculate the above mentioned indicators, field surveys were carried out in the studied headwaters at U, D and I transects at different dates during a calendar year. Prior of the measurements of channel morphology and hydraulics, the limits of the ‘active channel’ - which in these ephemeral systems includes the contemporary riparian zone (ecotone) - were identified (Bombino et al., 2009; Zema et al., 2018) (Table 2).

The physical surveys were carried out by a combination of topographic (for w/d, LS and q indicators), photographic (for $SD_{50}$ indicator), lab-grain size analytical (for SSF indicator) techniques applied to each transect. The indicators related to characteristics of riparian vegetation were calculated in proper sample areas across the transects, adopting the methods developed by Bombino et al. (2006; 2014) (Table 2).

### *2.2.4. Multivariate statistical techniques applied to the indicators*

Previously, a two-way analysis of variance ("ANOVA") was applied to evaluate the statistical significance of differences among the physical and vegetation parameters sampled at each transects, assuming as factors: (i) torrent (A, TG, SA, G); (ii) transect type (U, D, I); (iii) reciprocal interaction of torrent and transect.

All the sites were considered spatially independent in both cases. An independent Fisher's minimum significant difference test ("LSD") was used for the post hoc analysis comparisons. A $p < 0.05$ level of significance was adopted. Since ANOVA assumes normality in sample distribution, it was necessary to perform data log-transformations for the analysis, when this assumption was not respected after using Shapiro-Wilk's test.

Subsequently, the Principal Component Analysis ("PCA") was used to reduce the dimensionality of the data set of the indicators (correlated each other), loosing as little as possible information. By this way, we tried to identify a lower number of derivative and uncorrelated variables, called "principal components" (PCs), able to simplify the analysis of the highly complex processes standing behind check dam actions.

Finally, multiple regression models were built - separately for each transect group (U, D and I) - between the physical indicators on one hand (independent variables "x") and vegetation indicators on the other hand (dependent variables "y"); the biodiversity indicators were excluded in this processing step, since the correlations among the biodiversity and the physical/vegetal indicators were found to be weak (see the Results and Discussions section). The models were provided by the non-parametric Partial Least Square Regression ("PLSR") technique, a method for constructing predictive models when the factors are many and highly collinear. This technique was developed by Wold in the late 1960s for econometrics (Wold, 1975) and then extended to other scientific fields; it is an extension of multiple regression analysis, in which the effects of linear combinations of several predictors (in our case the morphological, hydraulic and sediment indicators) on multiple response variables (here, the indicators related to the riparian vegetation) are analyzed. Latent factors are extracted from predictor variables, maximizing the explained variance in the dependent variables, and defined as linear combinations, constructed between predictor and response variables; by this way, the original multidimensionality is reduced to a lower number of orthogonal factors to detect the structure in the relationships between predictor variables and between these latent factors and the response variables (Carrascal et al., 2009). The explanatory capacity of the models (that is, its prediction accuracy) was measured by the coefficient of determination ($r^2$).

All statistical analyses were performed using STATGRAPHICS and XLSTAT® release 2017.

## 3. RESULTS AND DISCUSSIONS

Zema et al. (2018) have demonstrated that, compared to the reaches located far from the check dams, the torrent control works influence significantly the unit discharge, surface and subsurface sediments (both upstream and downstream), channel shape and transverse distribution of riparian vegetation (upstream) as well as the cover and structure of riparian complexes (downstream). The actions of the control structures on torrent longitudinal slope and biodiversity of vegetation are less significant.

The 2-way ANOVA highlighted strong contrasts among the different transect types in both physical and vegetation indicators. As a matter of fact, the differences in morphological, hydraulic and sediment indicators as well as in the characteristics of the riparian vegetation were always significant (at $p < 0.05$) according to the transect positions with reference to check dam (Table 3 and Figure 2). This further confirms how much the control works significantly change cross section shape, hydraulic regime and bed sediment characteristics of headwaters as well as the development and biodiversity of the riparian vegetation, as already demonstrated through another statistical approach in the parent study by Zema et al. (2018). To summarise, the construction of check dams can cause changes in the morphological processes locally shaping the active channel, such as aggradation upstream and degradation downstream of the check dams (Bombino et al., 2014). As response to these morphological changes, the channel profile and width (as reflected by the modified w/d and LS indicators) are altered (Liu et al., 1992; Shieh et al., 2007; Boix-Fayos et al., 2007), which in their turn modify channel hydrology (reflected by changes in q). These hydromorphological adjustments play a role also in the sediment transport dynamics, enhancing deposition upstream of the check dam (with enrichment of the finer sediments, Bombino et al., 2008) and erosion downstream (Hooke and Mant, 2000; Galia et al., 2016). The riparian vegetation responds to these changes in channel hydro-morphology and bed sediment; thus the characteristics of riparian plant communities (structure, development and biodiversity) are be affected according to the prevailing geomorphic processes (Steiger et al., 2005) with differentiated magnitude according to the transect location (Bombino et al., 2009; 2014). The greater cover and height of riparian vegetation established in reaches located upstream of the check dams, acting as an obstacle against the water stream, slow down the water and sediment flows, thus modifying the hydraulic regime, and the erosion/sedimentation processes in the torrent. However, the biodiversity of riparian vegetation seemed to be much less influenced than the other vegetal characteristics, although the riparian communities are affected by the presence of the check dams (Bombino et al., 2014), showing higher species richness and evenness upstream of check dams and a parallel decrease of these biodiversity properties detected downstream (Zema et al., 2018).

When the physical and vegetation indicators were analysed considering as ANOVA-factor the geographic location (namely the torrent), many of these changes in channel hydrology, geomorphology and ecology induced by the check dam presence became not significant. More specifically, of the physical indicators, only the sediment characteristics of the channel bed varied significantly (at $p < 0.05$) among the studied torrents (Table 3 and Figure 2). Rather than to the prevalent texture and type and lithology of torrent soils (basically similar among the four headwaters, Table 1), this may be due to the different forest cover (broad leaves forests and mixed stands in Ionian and Tyrrhenian sub-watersheds, respectively) and soil lithology, which determined sediment fluxes from the adjacent hillslopes of different magnitude (solid discharge) and dimension (grain size) and thus different erosion/deposition processes within the active channel.

With regards to the vegetal indicators, the extension and the structure of riparian vegetation were quite similar among the studied torrents. Conversely, the vegetation characteristics linked to the biodiversity of riparian complexes were significantly different among the studied headwaters (Table 3 and Figure 2). As shown in Table 4, there is a prevalence of hygrophilous complexes in Tyrrhenian headwaters (mainly Gallico and, to a lesser extent, Sant'Agata), while the Ionian mountain sub-watersheds show a higher abundance of xerophilous plants (Allaro and Torbido di Gioiosa). These differences in riparian complexes biodiversity may be ascribed to the different climate characteristics of the individual headwaters, being the Tyrrhenian headwaters exposed to a higher humidity and the Ionian watersheds subject to longer drought conditions, which influence both species richness ($H_0$) and evenness ($H_2$), and their degree of integrity. This can be also shown by the differences in the temperature and rainfall gradients between Ionian and Tyrrhenian watersheds (Figure 3).

The interactions between the two ANOVA factors (torrent x transect) became significant only for two of the biodiversity indicators ($H_2$ and $Ns_A/Ns_N$), while the species richness (measured by $H_0$) of the riparian vegetation did not reflects the statistical significance of differences between headwater location and transect position (Table 3). No reciprocal effects across transects and watersheds were detected among the remaining physical and vegetation indicators.

The close relationships among the channel physical indicators and the resulting characteristics of riparian vegetation in proximity of check dams, detected in the previous study of Zema et al. (2018) were confirmed by the multivariate statistical analysis. These techniques appear to be feasible for the study, since they have been applied in many fields (e.g., Zema et al., 2015; Kazakis et al., 2018). Processing by PCA the set of the physical and vegetal indicators (most of which correlated each other, Zema et al., 2018), two derivative variables (Principal Components, PCs) were identified. These new variables explained over 75% of the variance in the data set (Figure 4); just the $PC_1$ (the first Principal Component) explained a variance equal to 59% of the total.

Very high loadings (indicating the extent to which the original indicators are influential or important in forming the PCs) of WCH, GCC, w/d and SSF (with positive values) as well as $CV_{GCC}$, $CV_{WCH}$, LS and q (with negative values) were found on $PC_1$ (Figure 5). These loadings highlighted a strong association between groups of physical and vegetation properties of the whole transect. The loadings of these indicators on $PC_2$ were quite low (< 0.303). Conversely, the loadings of $H_0$ and $H_2$ were low on $PC_1$ (< 0.449), but high on $PC_2$ (> 0.768); the indicator $Ns_A/Ns_N$ was moderately influential on both $PC_1$ (factor loading of -0.603) and $PC_2$ (0.627) (Figure 5).

As shown by PCA, $PC_1$ defines a strong gradient from low values of SSF, w/d, GCC and WCH (with negative loadings) to high values of $SD_{50}$, q, LS, $CV_{GCC}$ and $CV_{WCH}$ (with positive loadings) (Figure 5). Plotting the transect scores on the plan $PC_1$ - $PC_2$ shows that U, I and D transects fall in a sequence along this gradient; thus distinct contrasts in all of the morphologic, hydraulic and sediment parameters on one hand and most of the vegetation characteristics on the other hand are evident (Figure 5). This means that the first principal component ($PC_1$) is able to discriminate a transect group from another (that is, negative $PC_1$ for U transects, intermediate values for I and positive $PC_1$ for D zones) with only a limited overlap between the U and D transect groups; this allows the identification of a reach zone by a single derivative variable ($PC_1$) without adopting a larger set of indicators. Conversely, no clear gradient on $PC_2$ (associated with noticeable loadings to biodiversity characteristics of the riparian vegetation) was found among the transect groups, presumably due to the fact that the contrasts in the species richness and evenness among the transect locations with respect to the check dam are much less significant that physical parameters and the other vegetal characteristics (that is, cover, height and transverse variability), as 2-way ANOVA has demonstrated.

Table 5 reports the linear regression equations provided by PLSR applied to physical parameters - considered as independent variables (x), - and vegetation indicators - dependent variables (y). These equations, characterized by high explanatory levels ($r^2 > 0.695$ with a peak of 0.850), showed very different slope and intercept coefficients among groups of transects (U, D and I) (Table 4). Moreover, by analysing more deeply each one of the regression equations, the values of the slope coefficients suggests (Figure 6): (i) the influence of the physical changes on the riparian vegetation (explained by the value of the individual vegetal indicator "y" per unit variation of each physical parameter "x"); (ii) the difference of the riparian vegetation characteristics according to the transect location (explained by the differences in the coefficients among the transect groups). In our study torrents, as expected, the magnitude of the response of the riparian vegetation to the effects of physical adjustments due to the installation of check dams shows a gradient between upstream and downstream transects through the intermediate zones, as shown by the increasing values of the slope coefficients of the linear equations provided by PLSR (Figure 6). A sensitivity analysis applied to these equations could evidence by a greater detail the influence of each input parameter on the response of riparian vegetation to the physical adjustments generated by the presence of the check dams.

The fair explanatory capacity of the multi-regression models developed by the PLSR technique showed that, given the values of physical parameters, the extent, structure and transverse variability of riparian vegetation can be predicted with a high degree of accuracy and separately for different groups of transects.

Overall, the findings of our study try to remove the traditional approach based on field observations of the majority of studies about the effects of check dams on hydrological regimes, morphological changes, soil processes and torrent ecology. The predictive techniques developed in this study offer ~~offers~~ the possibility of a quantitative evaluation of the ecology response of torrents to the modifications induced by check dams. These predictions are necessary in order to inform the development of design criteria minimising the check dams impacts into fluvial dynamics and to define the desired state after restoration, preliminary to the correct restoration project design (Henry and Amoros, 1996).

## 4. CONCLUSIONS

This study applied multivariate statistical techniques to evaluate by a quantitative approach the local effects of check dams on morphology, hydrology, bed sediment oil and riparian vegetation of Mediterranean torrent headwaters.

The statistical analysis of the related indicators showed that physical adjustments of channels and most of the resulting characteristics of the riparian vegetation are specific for the transect locations with respect to check dam locations (upstream or downstream, and far from the direct influence of the structures). The geographic position of the studied watersheds determined statistically significant differences only for few physical (that is, those related to surface and subsurface sediment grain size) and biodiversity (that is, evenness and degree of integrity) indicators.

The regression equations between physical and vegetation indicators are complex, since these relationships are influenced by several factors of different nature (morphological, sedimentary, hydrological, and biological) and modified by the presence of the check dams. The application of Principal Component Analysis has simplified the comprehension of these relationships, providing a simple parameter (the first Principal Component), which is able to discriminate the physical and vegetal characteristics of torrents according to the transect group (upstream, downstream or intermediate).

The PLSR models proposed in this study are useful to predict the characteristics of riparian vegetation starting from the physical indicators surveyed in the different reaches of the torrents. These models may be very helpful: (i) to plan and design new check dams, since their the structure effects on the development and growth of vegetation upstream and downstream can be forecasted before their installation (at least for the quantification of the order of magnitude of the check dam impacts on torrent ecology); (ii) to delineate ecological scenarios after installing the river control works, which avoids *ad hoc* experimental tests at a real scale, needed to evaluate the effects that such works exert on the evolutionary tendency of the water course and riparian vegetation; (iii) to lower difficulties and uncertainties in the authorities' approval process for torrent control works; (iv) to comply with the requirements of the Water Framework Directive promoting integrated catchment management to achieve an optimum ecological state in river systems, with particular reference to the vegetation.

Overall, the relevant methodology applied in this study has proved to be sensitive and effective in isolating differences between transects and associations between physical and ecological variables around check dams. However, more research is needed to verify whether these methods are robust and appropriate for wider application to regulated rivers under different environments. To check this, future work should validate the proposed models in other water courses and control works with different characteristics, also assuring the largest repeatability of the experiments. If so, a useful tool for analysis and planning of future control works will be available for ecological restoration of water courses affected by intense human intervention, in view of returning them to a state as similar as possible to that which prevailed prior to disturbance.

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## TABLES

Table 1 – Headwater main characteristics of Allaro, Torbido di Gioiosa, Gallico and Sant'Agata torrents (Calabria, Southern Italy).

| **Characteristics** | **Allaro (A)** | **Torbido di Gioiosa (TG)** | **S. Agata (SA)** | **Gallico (G)** |
|---|---|---|---|---|
| *Climate* | | | | |
| *Average annual air temperature (°C)* (b) | 10.7±0.6 | 11.2±0.9 | 11.1±0.9 | 9.9±0.8 |
| *Average annual rainfall depth (mm)* (c) | 1780±550 | 1775±50 | 1351±50 | 1438±50 |
| *Morphology*(a) | | | | |
| *Area (km$^2$)* | 47 | 10 | 22 | 26 |
| *Maximum altitude (m.a.s.l)* | 1395 | 1215 | 1580 | 1730 |
| *Minimum altitude (m.a.s.l.)* | 1110 | 850 | 910 | 875 |
| *Length of main stream (km)* | 5.6 | 3.7 | 7.0 | 4.5 |
| *Land use* | | | | |
| *Main land use*(d) | Broad lived forest | Broad lived forest (Oakwood) | Mixed forest (Chestnut) | Mixed forest (Chestnut) |
| *Main aspect of vegetation* | Woodland | | | |
| *Main vegetation association* | *Alnetum glutinoso cordateae* | | | *Populetalia albae* |

| | | |
|---|---|---|
| *Soil* | | |
| *Main texture*(e) | Sandy loam | |
| *Main type*(e) | Humic Dystrudept | |
| *Main lithology*(f) | Granites and granodiorites | Micaschist, paragneiss, phyllite and marbles |

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[a] Estimated from 1:25000 scale maps

[b] Estimated from the relationships $T_m = 18.294 - 0.007A$ for the Ionian coast e $T_m = 16.913 - 0.006A$ for the Tyrrhenian coast, both developed using gauged data within the basins; where: $T_m$ = mean annual temperature in $^oC$; A = Altitude in m (average ± one standard deviation)

[c] Estimated by using the isohyetal method (average ± one standard deviation)

[d] Corine Land Cover (2012)

[e] USDA soil taxonomy classification (1999)

[f] Geological Map of Italy scale 1:50000 (1976)

Table 2 – Physical and vegetation indicators adopted in this study together with their significance and survey/calculation methods (from Zema et al., 2018).

| **Effect** | | **Indicator** | **Significance** | **Range of variability** |
|---|---|---|---|---|
| *Physical* | *Morphology* | w/d | Cross section shape | 0 ÷ ∞ |
| | | LS | Longitudinal slope | |
| | *Hydraulic* | q | Flow regime | |
| | *Sediment* | $SD_{50}$ | Surface sediment size | |
| | | SSF | Finer sub-surface sediment content | 0 ÷ 100% |
| *Vegetation* | *Development* | GCC | Extension | |
| | | WCH | Structure | 0 ÷ ∞ |
| | | $CV_{GCC}$ | Spatial distribution of extension | |
| | | $CV_{WCH}$ | Spatial distribution of structure | |
| | *Biodiversity* | $H_0$ | Species richness | |
| | | $H_2$ | Relative abundance | |
| | | $Ns_A/Ns_N$ | Degree of integrity | |

Table 3 – Two-way ANOVA applied to physical and vegetation indicators (measured in transects around 20 check dams) in the mountain reaches of Allaro, Torbido di Gioiosa, Gallico and Sant'Agata torrents (Calabria, Southern Italy).

| **ANOVA factor** | **Physical indicators** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | *w/d* | | *LS* | | *q* | | $SD_{50}$ | | *SSF* | |
| | F-ratio | P-value | F-ratio | P-value | F-ratio | P-value | F-ratio | P-value | F-ratio | P-value |
| *Transect* | 53.29 | <0.05 | 5.82 | <0.05 | 65.46 | <0.05 | 36.85 | <0.05 | 54.8 | <0.05 |
| *Torrent* | 1.04 | n.s. | 0.29 | n.s. | 1.84 | n.s. | 3.59 | <0.05 | 7.88 | <0.05 |
| *Interaction* | 0.41 | n.s. | 0.61 | n.s. | 0.64 | n.s. | 0.64 | n.s. | 0.88 | n.s. |

| **ANOVA factor** | **Vegetation indicators** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | *WCH* | | $CV_{GCC}$ | | $CV_{WCH}$ | | $H_0$ | | $H_2$ | |
| | F-ratio | P-value | F-ratio | P-value | F-ratio | P-value | F-ratio | P-value | F-ratio | P-value |
| *Transect* | 13.52 | <0.05 | 28.74 | <0.05 | 44.06 | <0.05 | 3.77 | <0.05 | 4.74 | <0.05 |
| *Torrent* | 1.29 | n.s. | 1.25 | n.s. | 1.57 | n.s. | 31.75 | <0.05 | 11.79 | <0.05 |
| *Interaction* | 0.18 | n.s. | 0.5 | n.s. | 0.83 | n.s. | 1.67 | n.s. | 3.78 | <0.05 |

Note: n.s. = not significant (at $p < 0.05$).

Table 4 – List of vegetation species surveyed in upstream (U), downstream (D) and intermediate (I) transects in the mountain reaches of Allaro (A), Torbido di Gioiosa (TG), Gallico (G) and Sant'Agata (SA) torrents (Calabria, Southern Italy).

| **Vegetation species** | **Torrents** | | | | **Vegetation species** | **Torrents** | | | |
|---|---|---|---|---|---|---|---|---|---|
| | *A* | *TG* | *SA* | *G* | | *A* | *TG* | *SA* | *G* |
| Acer neapolitanum | UDI | U | UD | UDI | *Calamintha grandiflora* | UD | UD | UD | |
| ***Alnus glutinosa*** | | | UD | UDI | ***Carex pendula*** | UD | | | UD |
| ***Fagus sylvatica*** | UI | UI | UI | UDI | Cerophillum temulum | U | U | U | |
| *Fraxinus oxicarpa* | UD | UD | UD | | Ceterach officinarum | DI | DI | DI | |
| *Pinus nigra ssp. Calabrica* | UD | I | UDI | | *Chenopodium album* | U | U | U | UD |
| ***Populus nigra*** | | | U | UDI | *Cynodon dactylon* | U | U | U | UDI |
| ***Salix alba*** | | | | UDI | *Dactylis glomerata* | DI | DI | DI | UDI |
| ***Salix brutia*** | U | U | UI | UDI | ***Digitalis purpurea*** | UDI | UDI | UDI | UDI |
| ***Salix caprea*** | UDI | UD | UI | UDI | ***Epilobium montanum*** | U | U | U | UD |
| Sambucus ebulus | UDI | | UI | UDI | Equisetum telmateja | U | U | U | UD |
| Sambucus nigra | U | UD | UI | UDI | Equisetum ramosissimum | U | U | U | |
| *Cytisus villosus* | D | D | D | | Foeniculum vulgare | D | D | D | DI |
| *Citysus scoparius* | DI | D | DI | UDI | Galium lucidum | D | | D | UDI |
| ***Clematis vitalba*** | U | | | UDI | Galium rotundifolia ssp. Hirs. | DI | | DI | UDI |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| ***Hedera helix*** | U | | UD | UDI | *Geranium robertianum* | UDI | | UDI | UDI |
| Ilex aquifolium | I | | I | UDI | *Inula viscosa* | UDI | UDI | UDI | UDI |
| Hypericum hircinum ssp. majus | UDI | UDI | UDI | | *Linaria purpurea* | UDI | UDI | UDI | UDI |
| *Rosa canina* | D | D | D | DI | ***Mentha acquatica*** | UI | UI | UI | UDI |
| ***Salix oropotamica*** | U | | | DI | ***Mentha suaveolens*** | U | U | U | UDI |
| ***Salix purpurea sub. Lamb.*** | UDI | UD | UI | UDI | *Parietaria diffusa* | D | D | D | |
| *Smilax aspera* | DI | DI | | | Poligonium lapatifolia | D | D | D | D |
| *Spartium junceum* | UDI | DI | DI | UDI | Polystichum setiferum | DI | DI | DI | DI |
| ***Tamarix gallica*** | | UDI | | | ***Ranunculus ficaria*** | UD | U | | UDI |
| *Achillea ligustica* | D | D | D | UD | *Saponaria officinalis* | DI | DI | DI | DI |
| ***Adiantum Capillus veneris*** | UDI | UDI | UDI | UDI | ***Tyipha latifolia*** | U | U | | UD |
| Angelica silvestris | UDI | | | UDI | Umbilicus rupestris | UDI | UDI | UDI | UDI |
| *Arum italicum* | UDI | | | UDI | Urtica dioica | UDI | UDI | UDI | UDI |
| *Brachipodium sylvaticum* | D | D | D | | | | | | |

Notes: the hygrophilous and xerophilous species are reported in bold and italic characters, while the remaining are mesophilous species.

Table 5 – Linear regression coefficients and models' predictions accuracy provided by Partial Least Squared Regression between couples of physical (independent variables, x) and vegetal (dependent variables, y) indicators (measured in transects around 20 check dams) in the mountain reaches of Allaro, Torbido di Gioiosa, Gallico and Sant'Agata torrents (Calabria, Southern Italy).

| **Model parameter/ explanatory capacity** | | **Transect group** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Upstream** | | | | **Downstream** | | | | **Intermediate** | | | |
| | | *Dependent variable (y)* | | | | | | | | | | | |
| | | *GCC* | *WCH* | $CV_{GCC}$ | $CV_{WCH}$ | *GCC* | *WCH* | $CV_{GCC}$ | $CV_{WCH}$ | *GCC* | *WCH* | $CV_{GCC}$ | $CV_{WCH}$ |
| *Independent variable (x)* | *w/d* | 0.431 | 0.032 | -0.164 | -0.134 | 1.069 | 0.073 | -0.741 | -0.537 | 0.797 | 0.050 | -0.877 | -0.986 |
| | *LS* | -72.216 | -5.397 | 27.522 | 22.534 | -161.043 | -11.048 | 111.516 | 80.895 | -130.071 | -8.086 | 143.229 | 160.958 |
| | *q* | -2.318 | -0.173 | 0.883 | 0.723 | -0.762 | -0.052 | 0.528 | 0.383 | -1.250 | -0.078 | 1.377 | 1.547 |
| | $SD_{50}$ | -0.092 | -0.007 | 0.035 | 0.029 | -0.033 | -0.002 | 0.023 | 0.017 | -0.059 | -0.004 | 0.065 | 0.073 |
| | *SSF* | 0.407 | 0.030 | -0.155 | -0.127 | 0.359 | 0.025 | -0.249 | -0.180 | 0.398 | 0.025 | -0.439 | -0.493 |
| *Intercept* | | 44.520 | 2.336 | 19.812 | 17.814 | 43.988 | 2.426 | 23.293 | 31.159 | 46.524 | 2.523 | 36.382 | 32.926 |
| *Accuracy* | $r^2$ | 0.749 | 0.850 | 0.695 | 0.715 | 0.759 | 0.797 | 0.785 | 0.711 | 0.757 | 0.742 | 0.753 | 0.832 |

Note: acronyms of indicators are reported in Table 2.

# FIGURE CAPTIONS

Figure 1 - The locations of the four study watersheds (“A” Allaro, “TG” Torbido di Gioiosa, “G” Gallico and “SA” Sant’Agata).

Figure 2 - Plots of physical and vegetation indicators measured in transects around 20 check dams in the mountain reaches of the Allaro, Torbido di Gioiosa, Gallico and Sant'Agata torrents (Calabria, Southern Italy) – (a) physical indicators; (b) vegetation indicators.

The horizontal and vertical bars measure the variability by the normalized root-mean-square deviation (NRMSD) among transects and torrents, respectively, with respect to the mean value of each indicator. NRMSD is calculated dividing the x or y standard deviations by the difference between the maximum and the minimum ($x_{max}$ - $x_{min}$ or $y_{max}$ - $y_{min}$) values of the indicator.

Figure 3 - Walter and Lieth diagrams (mean temperature and precipitation) of the meteorological stations of Gambarie di Aspromonte (a, m 1316 a.s.l., years 1974-2015) and Croce Ferrata (b, m 970 a.s.l., years 1979-2011) (Calabria, Southern Italy).

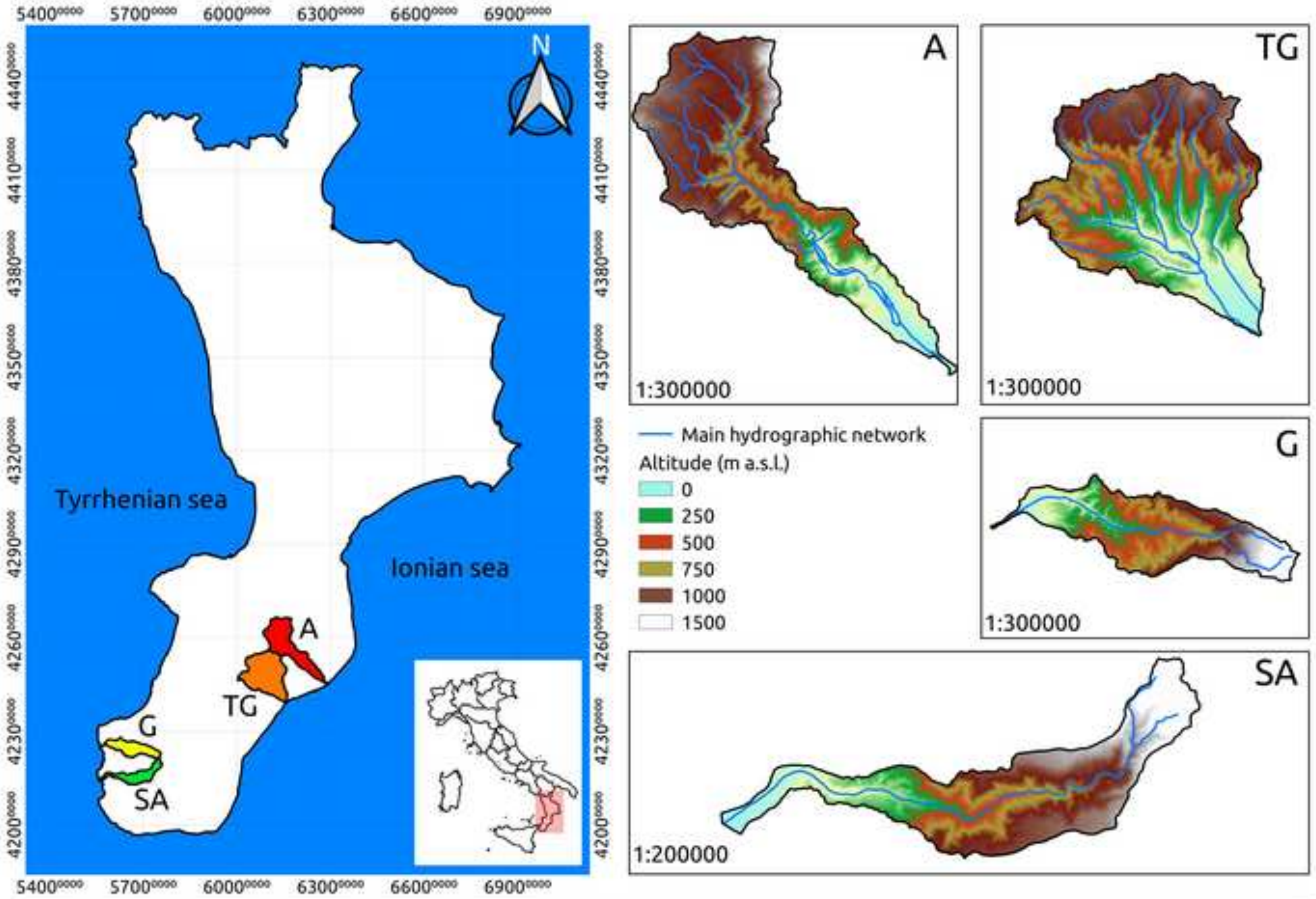
Figure 4 - Loadings of physical and vegetation indicators on the first two principal components ($PC_1$ and $PC_2$) of PCA around 20 check dams in the mountain reaches of Allaro, Torbido di Gioiosa, Gallico and Sant'Agata torrents (Calabria, Southern Italy).

Figure 5 - Plot of transect scores on the first two principal components ($PC_1$ and $PC_2$) derived by PCA applied to the physical and vegetation indicators (measured in transects around 20 check dams) in the mountain reaches of Allaro, Torbido di Gioiosa, Gallico and Sant'Agata torrents (Calabria, Southern Italy).

Figure 6 - Scatter plots of observations against predictions by multiregression models provided by Partial Least Square Regression applied to the physical and vegetation indicators (measured in transects around 20 check dams) in the mountain reaches of Allaro, Torbido di Gioiosa, Gallico and Sant'Agata torrents (Calabria, Southern Italy).

5% and 95% confidence interval are reported as filled grey lines.

**Figure 1**



"A": Allaro; "TG": Torbido di Gioiosa; "G" Gallico; "SA": Sant'Agata

Figure 2a

Click here to download high resolution image

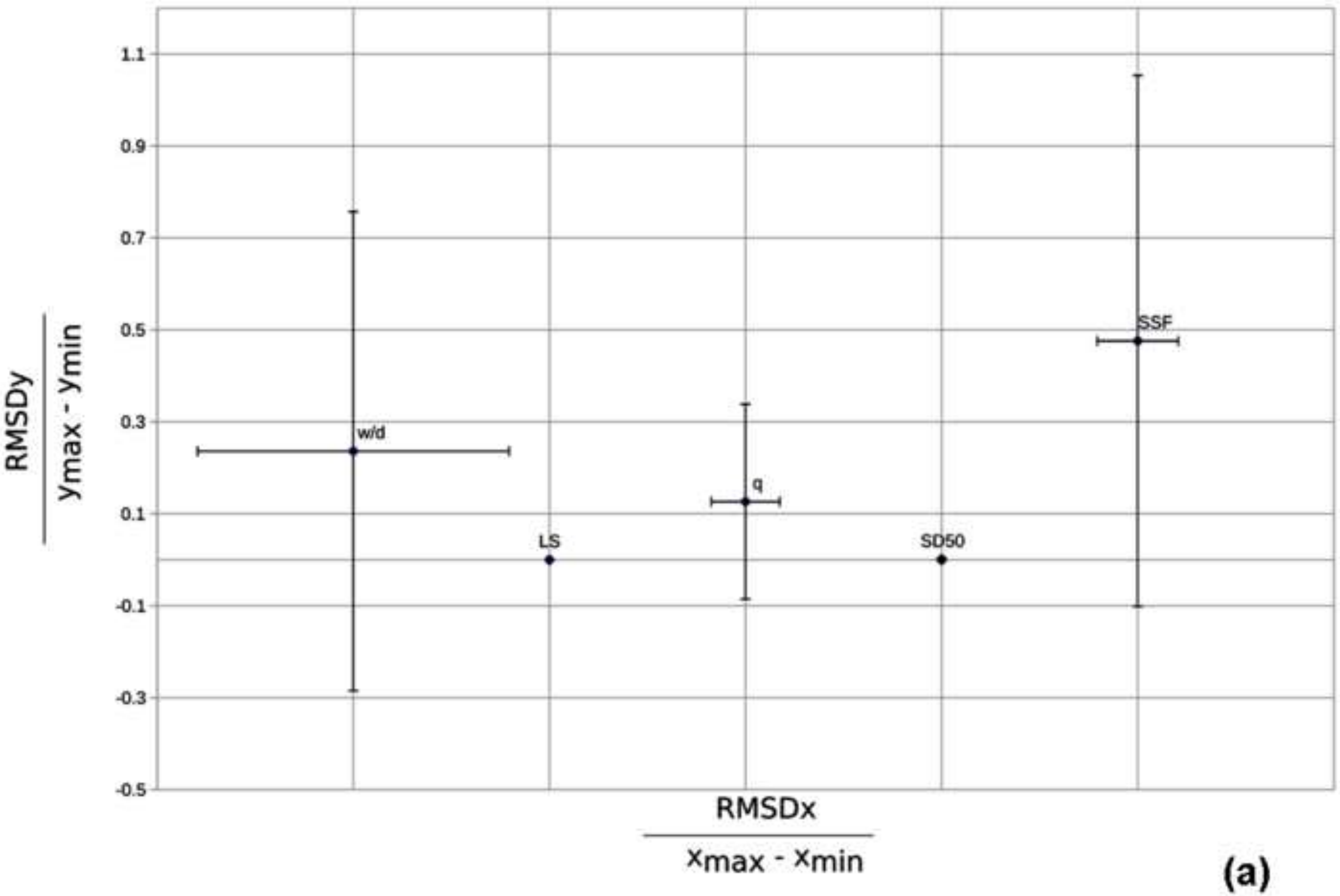
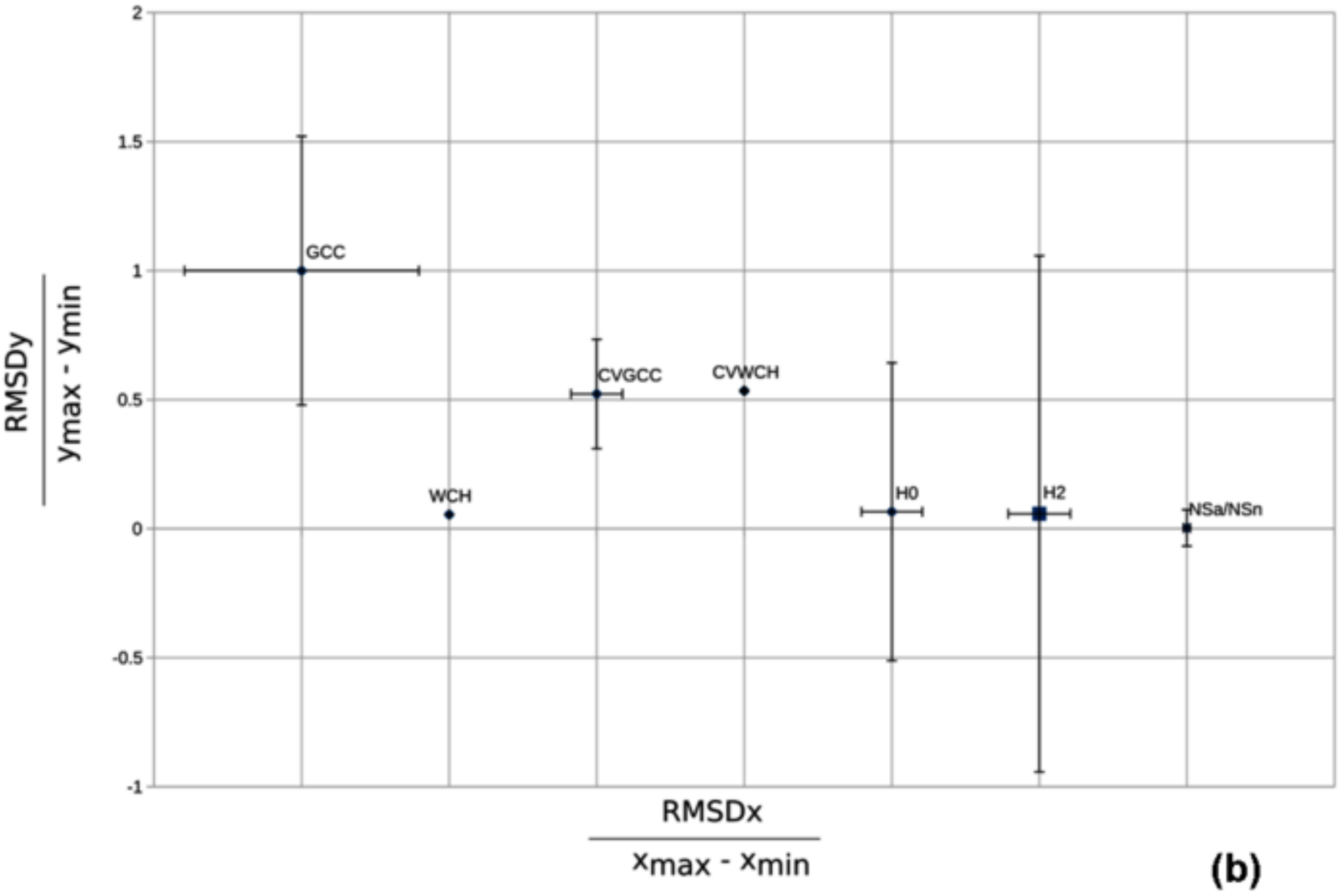


Figure 2b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1.5
1
0.5
0
-0.5
-1
GCC
WCH
CVGCC
CVWCH
H0
H2
NSa/NSn
RMSDy / Ymax - Ymin
RMSDx / Xmax - Xmin
(b)

Figure 3a

Click here to download high resolution image

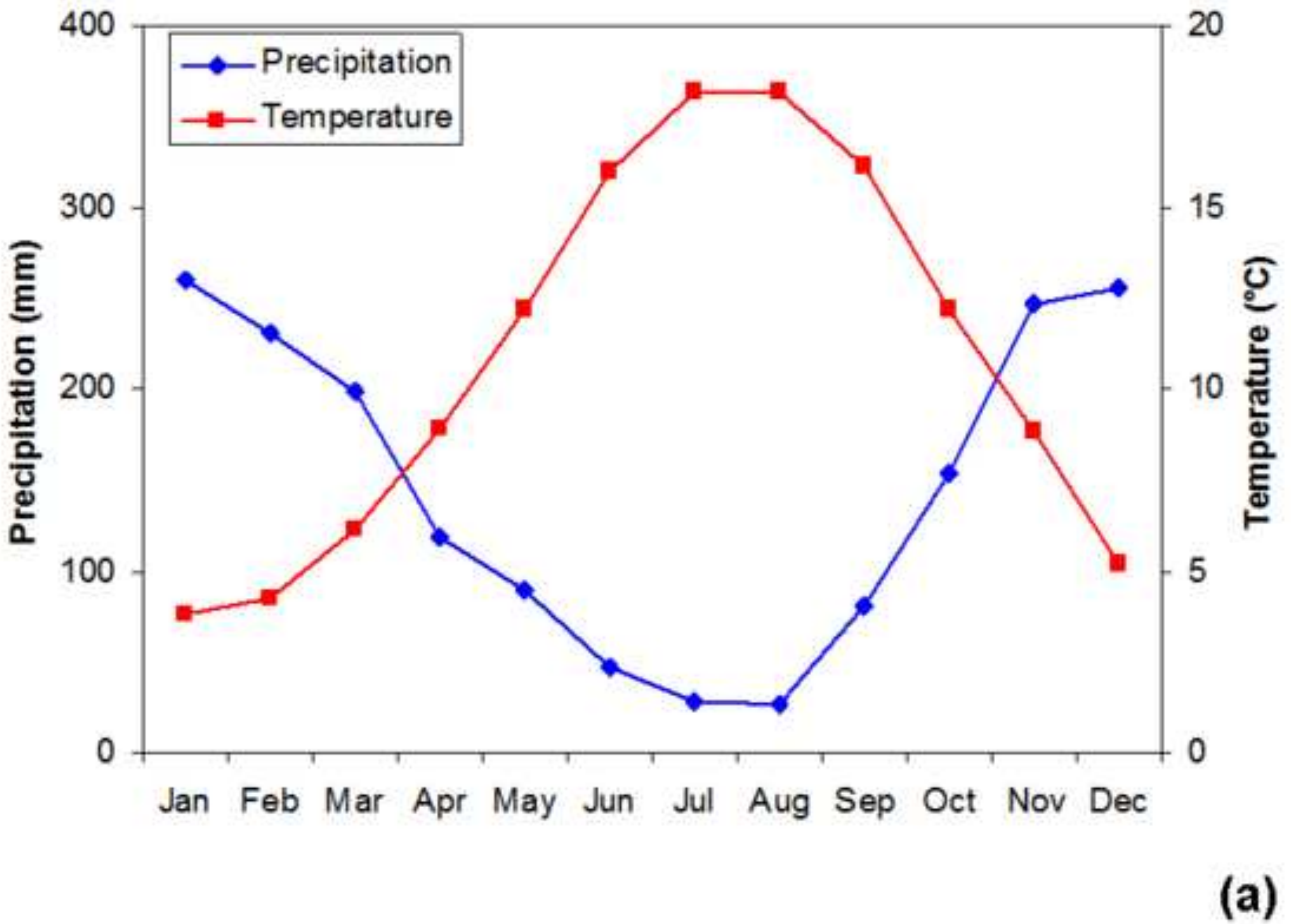


**Figure 3b**

**Click here to download high resolution image**

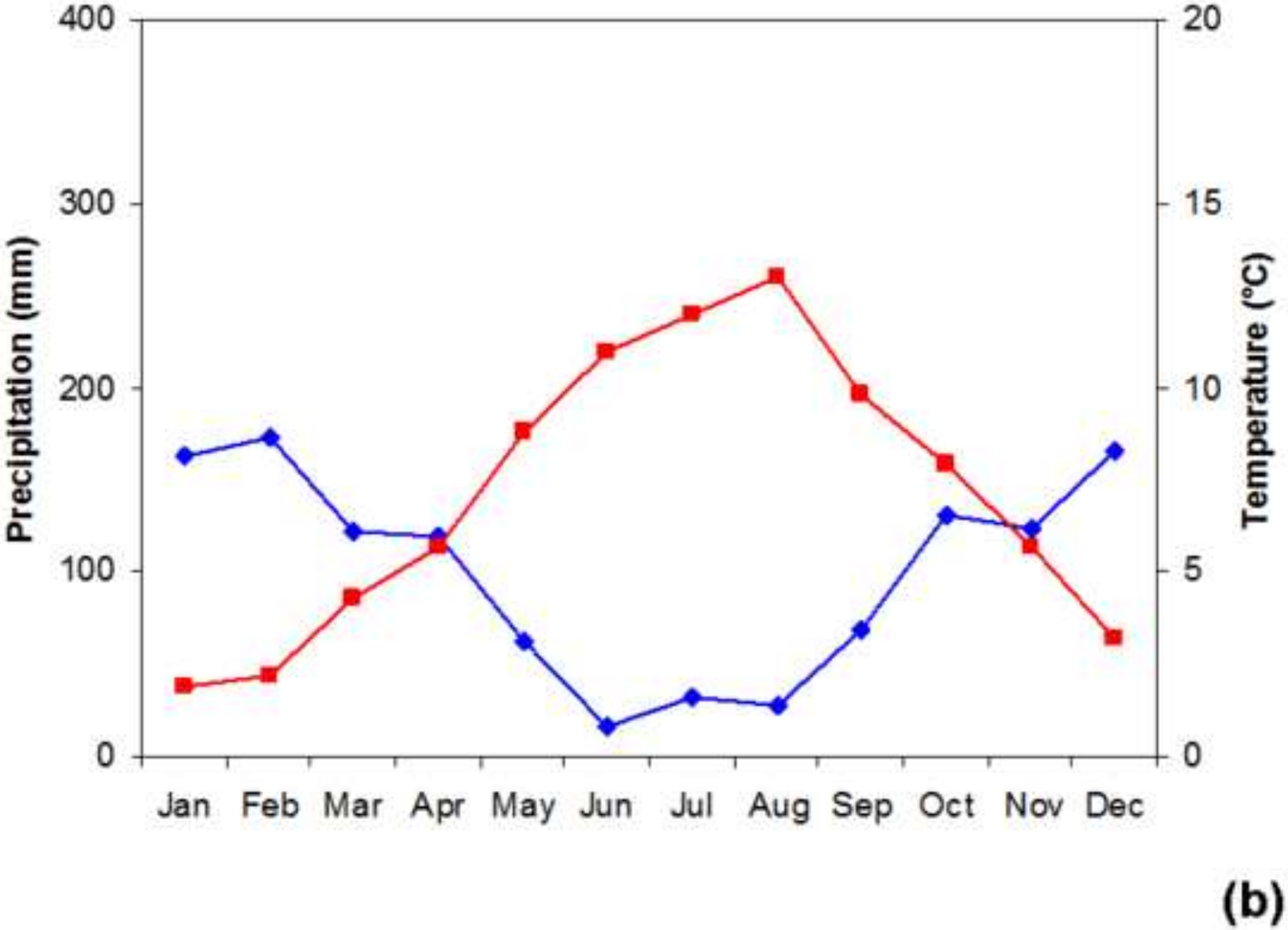
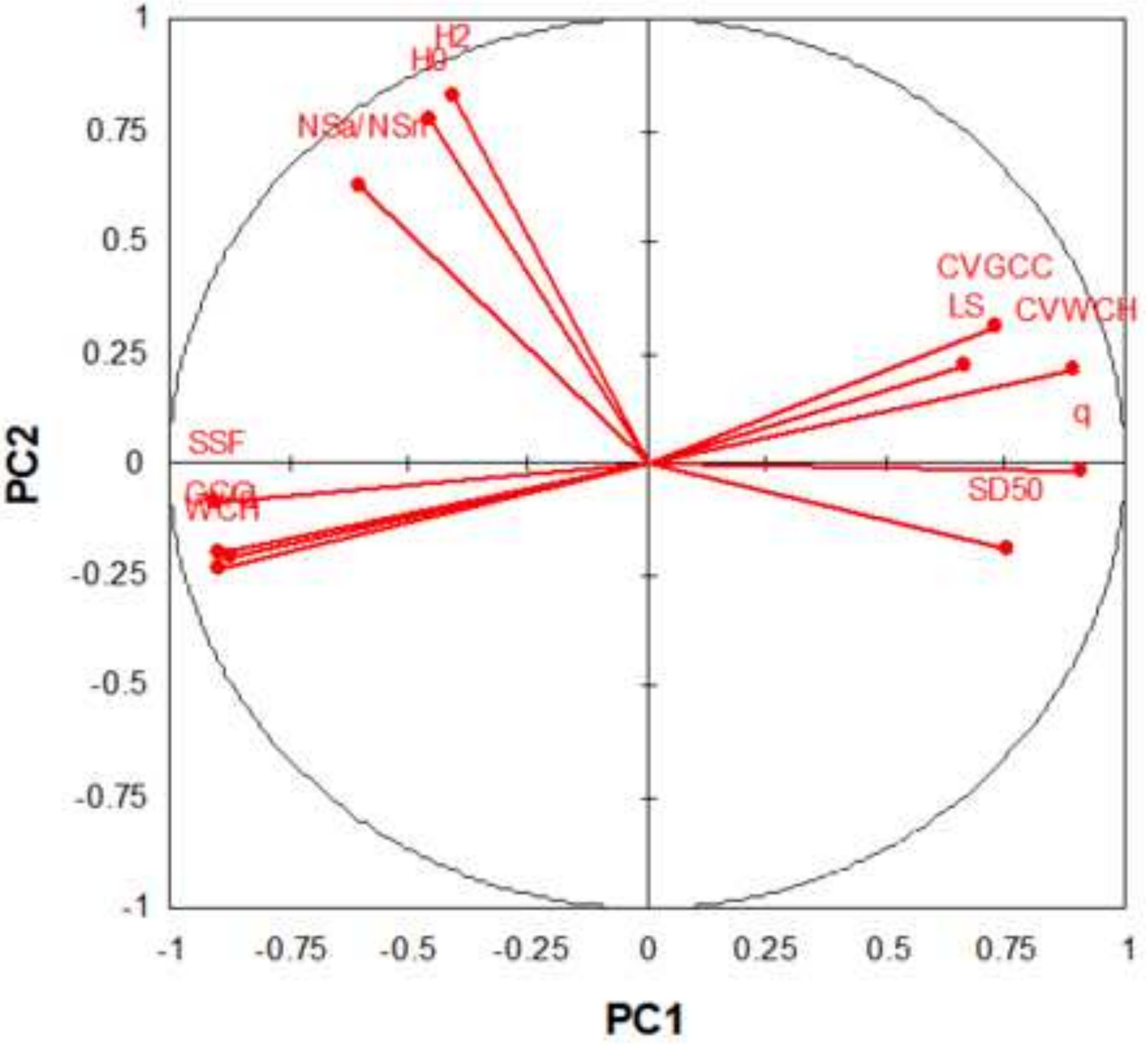


Figure 4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H0
NSa/NSn
CVGCC
LS
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q
SSF
GCC
WCH
SD50
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0.75
0.5
0.25
0
-0.25
-0.5
-0.75
-1
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1
PC2
PC1

**Figure 5**

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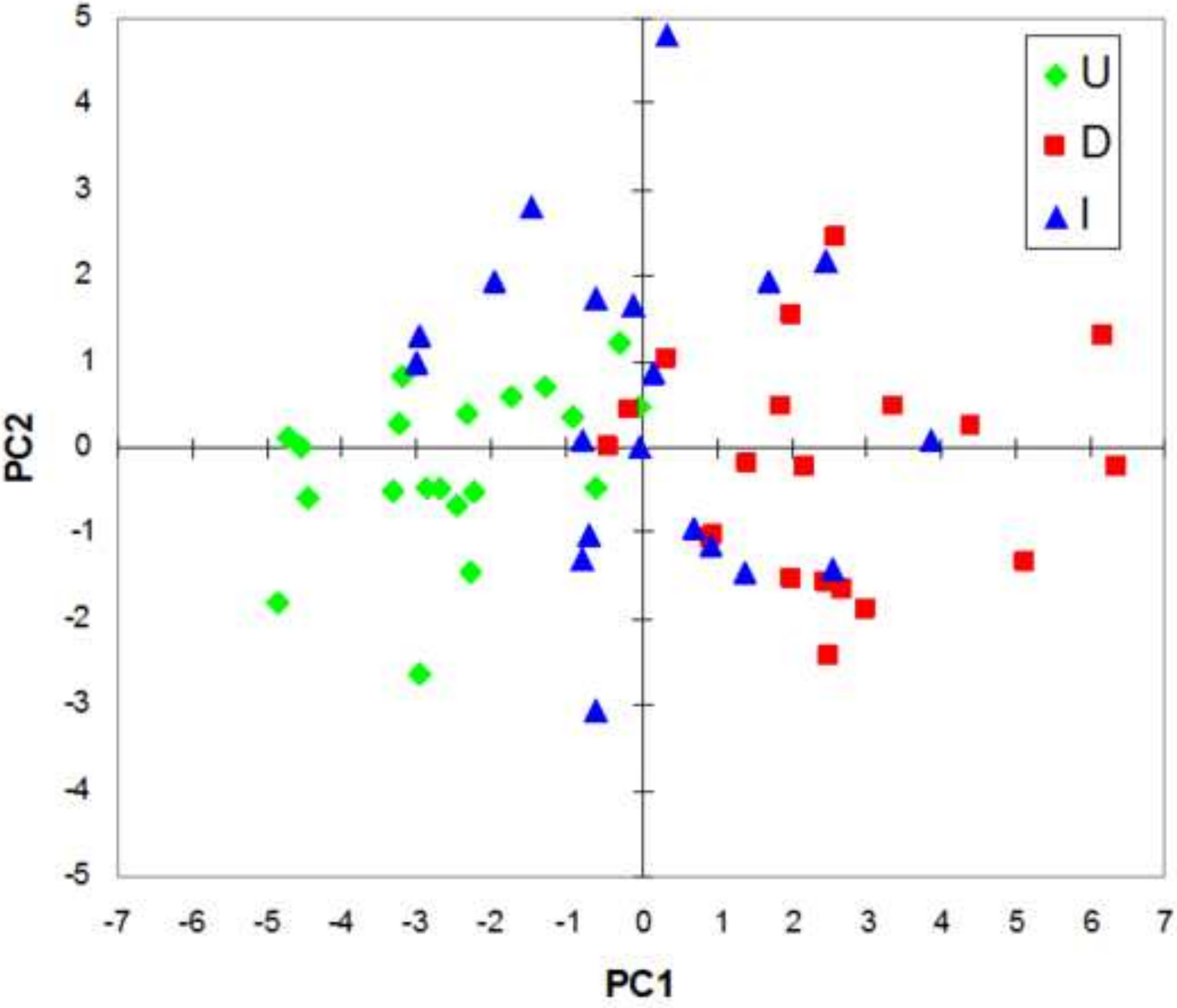
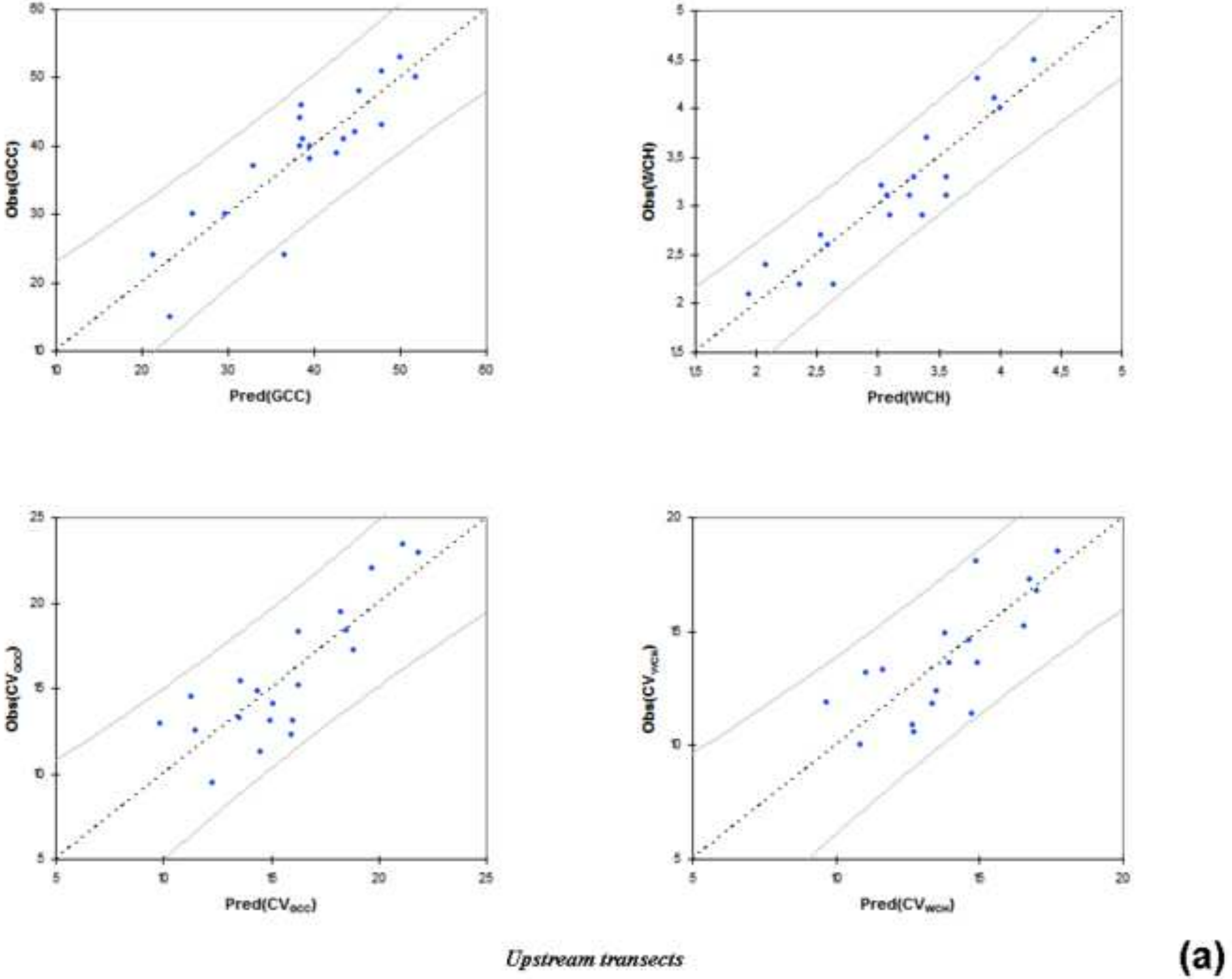


**Figure 6a**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Pred(GCC)
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20
30
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50
60
Obs(WCH)
Pred(WCH)
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2
2,5
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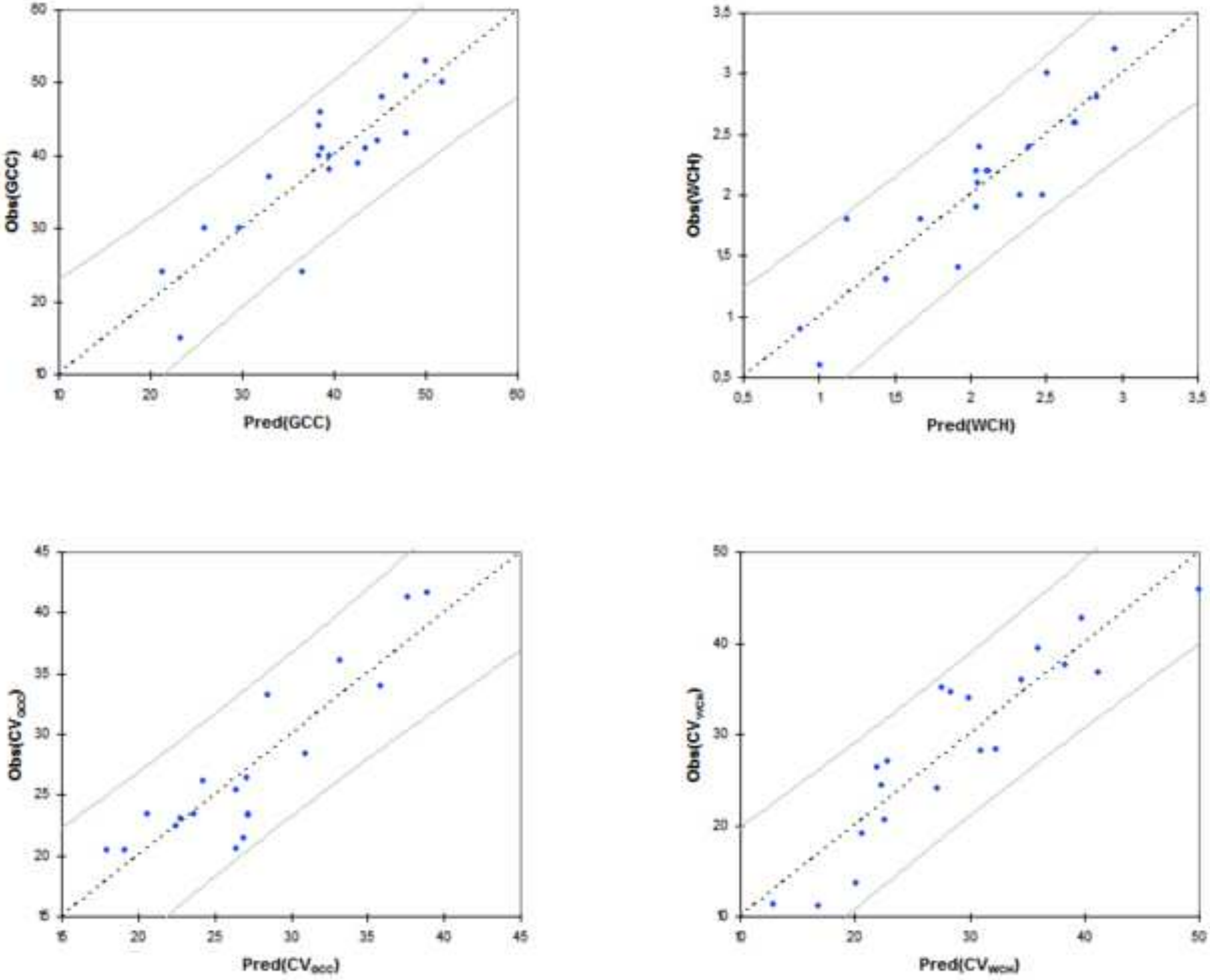
4
4,5
5
Obs(CV_GCC)
Pred(CV_GCC)
5
10
15
20
25
Obs(CV_WCH)
Pred(CV_WCH)
5
10
15
20
Upstream transects
(a)

Figure 6b



*Downstream transects*

**(b)**

**Figure 6c**

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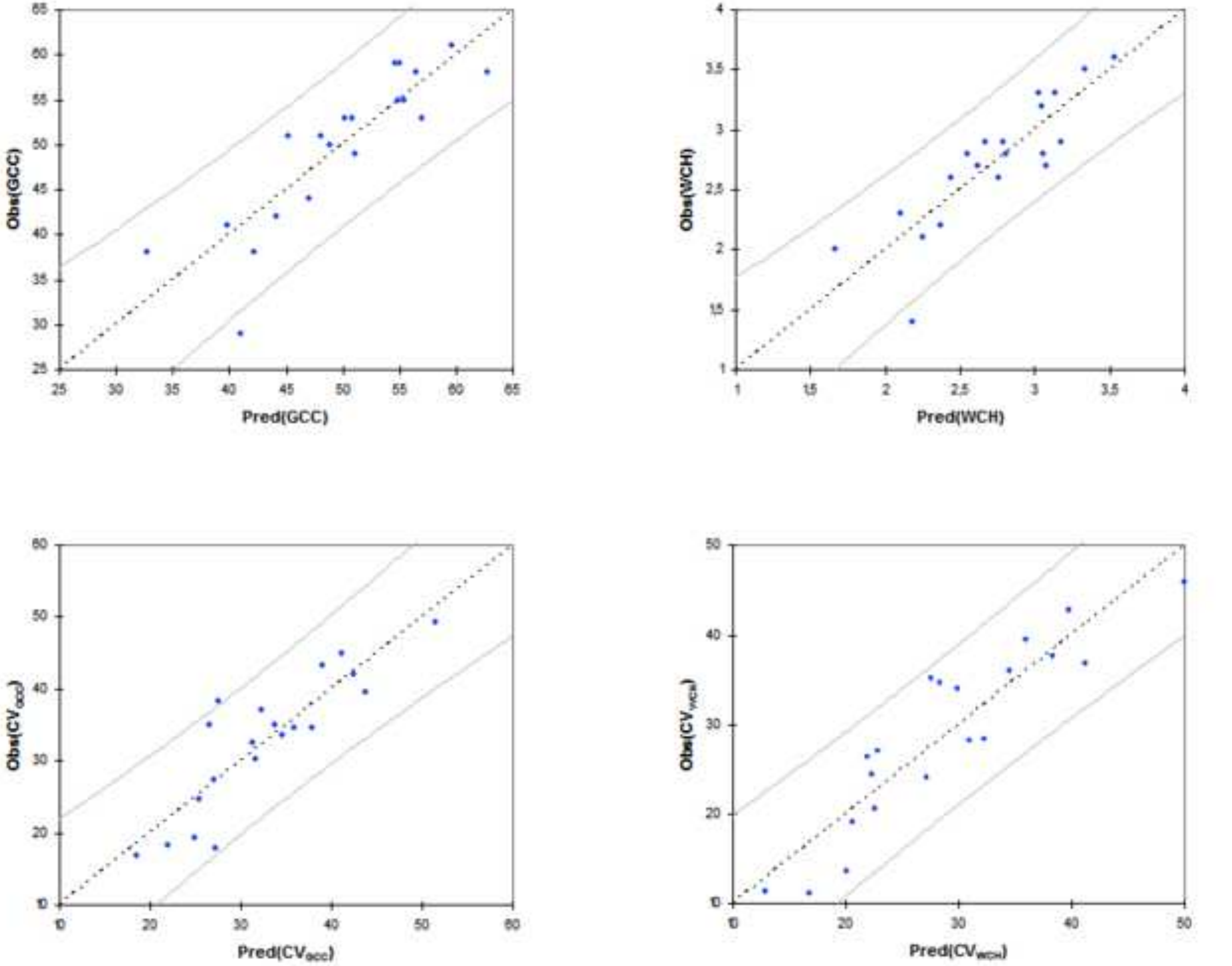

*Intermediate transects*

**(c)**