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Linear Bivariate Expressions for Marine Benthic Macrophytes Ecological Status Description

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Abstract Regarding ecological status assessment with marine benthic macrophytic indicators as per European Water Framework Directive (WFD), linear models are being reviewed (either starting from discontinuous forms or modifying quadratic and algebraic forms). Through use of simple concepts, model flexibility is demonstrated in terms of application to different indicators and varying marine environments. Four variants of the Ecological Evaluation Index (EEI) approach yield similar results (same or adjacent ecological status classifications in 18 out of 20 points) for a Saronikos Gulf data set; they are further compared with variants of the Quality of Rocky Bottoms (CFR) approach over WFD-related aspects (ecological status classification, coverage, richness).

Keywords: Water Framework Directive, marine benthic macrophytes, CFR model, RPI approach for EEI model

1. Introduction

The European Water Framework Directive (WFD) lists aquatic flora among biological quality elements for coastal waters ecological status description (EC, 2000). Composition and abundance indicators for marine benthic macrophytes are used in formulae with few independent variables, providing continuous, monotonic Ecological Quality Ratio (EQR) values (non-decreasing in the [0, 1] range). This work considers bivariate model aspects, relevant to WFD provisions for ecological status assessment: reference-domain (independent variables plane) partitioning over the 5 types of ecological status classification (ESC) and behavior near the axes origin (diminishing macrophytic cover). Discontinuous original Ecological Evaluation Index (EEI) model (Orfanidis *et al*., 2001) is modified, here, into a continuous linear form (l-EEI), using concepts of the linear, bivariate RPI approach (Tzouvaras, 2018), introduced as an alternative to the (quadratic) continuous EEI (Orfanidis *et al*., 2011); ecological status assessment is carried out here for a 20-point data set with the four variants. Aspects of the Quality of Rocky Bottoms (Calidad de Fondos Rocosos; CFR) model, at first discontinuous (Juanes *et al*., 2014) and currently in algebraic form (Guinda *et al*., 2014) are compared, in this work, with those of EEI variants.

2. Methods and materials (Model considerations)

2.1. EEI model

The bivariate EEI model, applied to transitional and coastal waters in the Mediterranean ecoregion (Kosmidou et al., 2019) , classifies macrophytes in two Ecological State Groups (ESGs): late-successional / perennial (ESG I) and opportunistic / annual (ESG II) ones. Drawing upon a model applied to description of eutrophic conditions in estuaries by means of two aggregated indexes (Bricker *et al*., 1999), the original EEI (henceforth, o-EEI) variant (Orfanidis *et al*., 2001) uses a cross-comparison matrix of ESG values (determined as substrate percentage coverage by macrophytes, considering various growth forms that may lead to values exceeding 100%) yielding EEI values expressed in terms of 5 (even) integers in the range [2, 10], corresponding to the 5 ESCs ("High", "Good", "Moderate", "Poor", "Bad"; respective color code: blue, green, yellow, orange, red), that are further converted to discrete EQR values in [0, 1]. In addition to discontinuity of EQR values, a checkered-like partitioning of the reference-domain renders the pertinent areas non-convex.

The continuous EEI formula (henceforth, EEI-c) uses an optimization procedure to express EEI as a quadratic function of ESG I (x-coordinate) and ESG II (y-coordinate); EQR is calculated through a linear transformation (Orfanidis *et al*., 2011). Although the pertinent quadratic surface is substituted by horizontal planar segments for certain regions of the reference-domain (including those corresponding to independent variables values ≥ 150), so as to ensure that EEI remains bounded in the [2, 10] range and to limit effects of a saddle-point (in the [100, 150] range of independent variables values), the EEI-c achieves continuity and substantially limits the non-convex nature of reference-domain partitioning, in comparison with o-EEI.

As an alternative to EEI-c, a linear approach, RPI (Reference-domain Partitioning through Inclines), has been suggested (Tzouvaras, 2018), based on: (1) partitioning the reference-domain (plane of independent variables, as x=ESG I and y=ESG II) over the 5 ESCs by means of line segments, producing convex regions and (2) replacing the quadratic surface of EEI-c by an overarching linear composite surface (expressing the dependent variable z=EQR) that consists of alternating planar segments: horizontal and inclined ones.

Figure 1 contains elements of the RPI approach (x=ESG I and y=ESG II in the [0, 100] range), including: (a) a sketch of the overarching linear composite surface (with white Inclines and with horizontal segments in color); (b) the reference-domain (independent variables plane, for z=EQR=0) partitioned over the 5 ESCs (including an area corresponding to the projection of the EQR=1 segment, shown in dark blue color, representing Reference Conditions at x=ESG I values close to 100); (c) the coefficients of the Separating Lines (expressed as y=A*x+B) that partition the reference-domain; (d) the projection of the overarching linear composite surface onto the reference-domain (projections of its horizontal segments are shown in color); (e) the coefficients of the Intersection Lines (expressed as y=A*x+B, except for x=4 for the line appearing first in the list) that form the projection of the overarching composite surface onto the reference-domain; (f) the coefficients of the expressions that describe the planar segments of the overarching composite surface (expressed as EQR=z=A*x+B*y+C), using color-coding for the horizontal segments and for the Inclines (white); (g) an example for EQR determination, corresponding to ESG I=50% and ESG II=85% (x=ESG I; y=ESG II, z=EQR). The common slope of the Inclines with respect to variable x is set as 0.025.

The concept of inclines is applicable directly to o-EEI, overcoming discontinuity (Tzouvaras, 2019), although reference-domain partitioning to convex regions appears not to be achieved, unless the pertinent horizontal segments disappear. In such a procedure, a plane expressed as EEI=0.04*(ESG I) - 0.04*(ESG II) + 6, would yield EEI values in the [2, 10] range, with the independent variables in the [0, 100] range, as in o-EEI.

As an alternative to o-EEI, a linear composite surface with five planar segments is possible to establish, as shown in the present work, leading to a linear model (henceforth, "l-EEI") that provides continuous EQR values in the [0, 1] range directly (rather than through EEI values) and achieves reference-domain partitioning into five convex regions (representing ESCs), that retain the pertinent trend of o-EEI. The boundaries of ESCs are set at EQR values of 0.2, 0.4, 0.6 and 0.8, as is also valid for the RPI approach; respective boundaries for EEI-c are 0.04, 0.25, 0.48 and 0.76 (Orfanidis *et al.*, 2011).

Figure 2 contains pertinent elements: (a) for o-EEI, (b) to (e) for l-EEI and (f) for EEI-c. These are: (a) the matrix concept for o-EEI; (b) the reference-domain (independent variables plane, for z=EQR=0) for l-EEI, partitioned over the 5 ESCs (including areas corresponding to EQR=0 and EQR=1, the latter representing Reference Conditions at x=ESG I values close to 100); (c) for l-EEI, the coefficients of the lines (expressed as y=A*x+B) that partition the reference-domain into the 5 ESCs, using appropriate color-coding; (d) for l-EEI, a side-view (-45° direction) of the linear composite surface reflecting its five planar segments and indicating the 5 ESCs; (e) for l-EEI, the coefficients of the equations for the five planar segments of the linear composite surface (expressed as EQR=z=A*x+B*y+C), using appropriate color-coding; (f) the partitioning of the reference-domain for EEI-c (with ex post replacements of quadratic surface parts by horizontal segments; their projections are marked as dark red for EQR=0 and as dark blue for EQR=1).

2.2 CFR model

As with o-EEI, a similar application has been considered (Tzouvaras, 2019) regarding the original, discontinuous (ranges-based) CFR model, introduced for coastal waters in the NE Atlantic ecoregion and involving four constituents (Juanes *et al.*, 2008): R (richness), O (opportunistic species relative cover), C (macroalgal cover), S (physiological status). Combination of C and O components in a matrix, comparable to that in o-EEI, allows a continuous expression of their combined values, mending the model's inability to express (in two decimal figures) all the EQR values in [0, 1].

The CFR model has been subsequently elaborated into an essentially linear, continuous form (Guinda *et al.*, 2014), using three components: C (percentage coverage of "characteristic macroalgae"), F (weighed fraction of opportunistic species) and R (richness of "characteristic macroalgae"). The "Flat Intertidal" version of continuous CFR is considered here; from a list of 24 "characteristic macroalgae" determining C, the number of those with >1% substrate area coverage provides the richness value, i.e. R, as an integer in [0, 10], with 10 representing Reference Conditions. ESCs boundaries are set at EQR values of 0.2, 0.4, 0.6 and 0.81, respectively.

Therefore, R may obtain a limited number of discrete (integer) values and, for constant R, the features of continuous CFR reflect those of a bivariate model. The reference-domain (defined by characteristic macroalgae (C) and opportunistic species fractional percentage coverage (F), these being considered here as the independent variables) is split into 6 areas by means of 3 additional Reference Condition values: 5% and 40% for F and 90% for C. Therefore, an overarching linear composite surface is formed, that provides EQR values.

Figure 3 presents pertinent elements for R=5, namely: (a) a projection of the linear composite surface, expressing EQR, on the reference-domain with C and F as independent variables, in line with the configuration of the model, demonstrating the regions of the 5 ESCs and (b) the equations for the 6 planar segments of the composite surface (expressed as EQR=z=A*x+B*y+C), using appropriate number-coding.

3. Results and Discussion

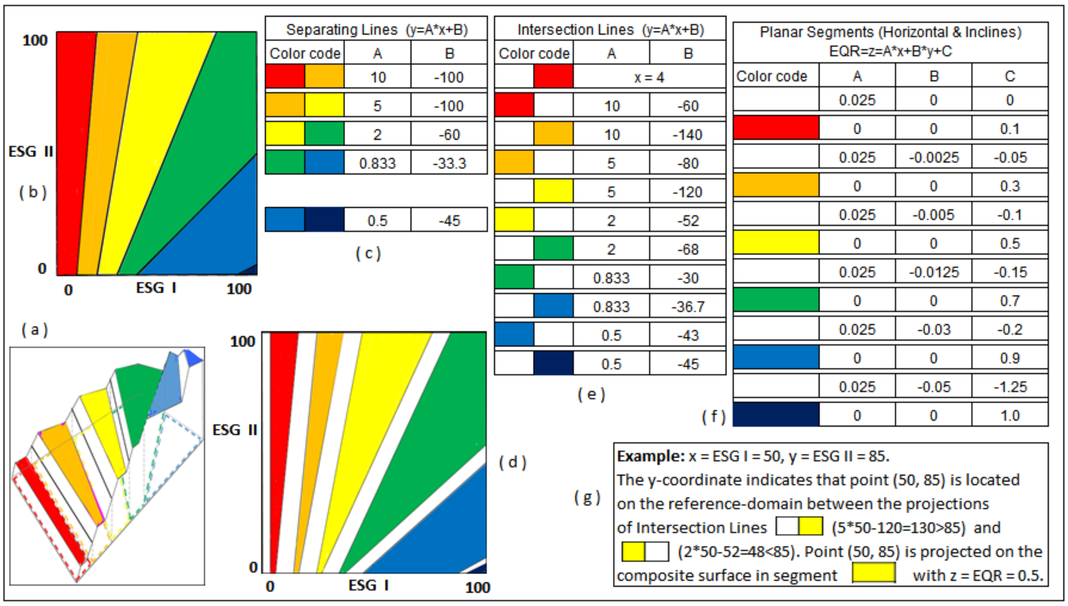
For the EEI variants, Figure 4(a) presents results obtained here, as ESC classification, for a set of 20 data points from Saronikos Gulf (Orfanidis *et al.*, 2001), for o-EEI, EEI-c, the RPI approach and l-EEI. The four variants provide identical ESCs for 5 samples, while for another 13 samples adjacent ESCs are obtained. The 3 continuous variants (EEI-c, RPI and l-EEI) provide identical ESCs for 10 samples. Compared with o-EEI individually, the 3 continuous variants match in 13 (EEI-c) or 10 (RPI and l-EEI) samples. It is noted that EEI-c has been developed as an upgrade from o-EEI. On the other hand, RPI was suggested as an EEI-c alternative, providing identical ESCs with it in 15 out of the 20 samples. The overall outcome is fairly good, noting also that several coverage values exceed 100% (considering that the four variants differ, in regard to such extrapolations).

For the CFR model, following calculations carried out here, Figure 4(b) presents (for all R values in [0, 10]) overlapping projections, on the reference-domain, of the corresponding linear composite surfaces, demonstrating the split into the 5 ESCs. Various model features have been taken into consideration (C≥R, numerically; C≤24 for R=0). As R increases, the stepwise contraction of ESC "Bad" (disappearing for R values exceeding 7) and expansion of ESC "High" (with EQR reaching 1 for R=10, shown in dark blue color and relating to Reference Conditions) are evident, while the convex nature of these two regions is retained (contrary to the remaining ones).

With respect to reference-domain percentage assignment to ESC "Bad", in the independent variables [0, 100] range, the RPI approach, featuring 15%, appears to relate to CFR partitioning for R=4; similarly, EEI-c assigns 6.4% of the reference-domain area to ESC "Bad" and appears relating to R=6. The models also vary regarding their behavior when macroalgal coverage tends to 0 (axes origin on the reference-domain). RPI has been developed so as to yield ESC "Bad" (EQR=0); l-EEI leads to ESC "Moderate" (EQR=0.5), as does o-EEI (Simboura *et al.*, 2005); CFR predicts ESC "Poor" (EQR=0.35), shown in Fig. 4(b) for the R=0 projection. EEI-c applies to vegetated (% coverage > 10%) areas (Orfanidis *et al.*, 2011); however, at the independent variables axes origin its analytical expression would yield an outcome relating to ESC "Moderate" (EQR would equal 0.468, with the ESC "Moderate" range being [0.25, 0.48]).

4. Conclusion

For macroalgal ecological status description by bivariate, linear expressions as the RPI approach (introduced as an alternative to EEI-c), simple, linear models (such as l-EEI developed here) are directly derivable from discontinuous o-EEI. Tested with a literature data set, the three continuous variants (EEI-c, RPI and l-EEI) perform comparably. RPI approach characteristics (overarching linear composite surface and inclines) are evident in an analysis of CFR, a linear, trivariate model (with features conditionally comparable to EEI variants'), developed for a separate ecoregion. This fact indicates the flexibility of the RPI approach, as well as a potential for application in terms of expressions with three variables, deriving or combining EQR values for ecological status assessment.



Separating Lines (y=A*x+B)		
Color code	A	B
🟥🟧	10	-100
🟧🟨	5	-100
🟨🟩	2	-60
🟩🟦	0.833	-33.3
🟦⬛	0.5	-45

(c)

Intersection Lines (y=A*x+B)		
Color code	A	B
⬜🟥	x = 4	
🟥⬜	10	-60
⬜🟧	10	-140
🟧⬜	5	-80
⬜🟨	5	-120
🟨⬜	2	-52
⬜🟩	2	-68
🟩⬜	0.833	-30
⬜🟦	0.833	-36.7
🟦⬜	0.5	-43
⬜⬛	0.5	-45

(e)

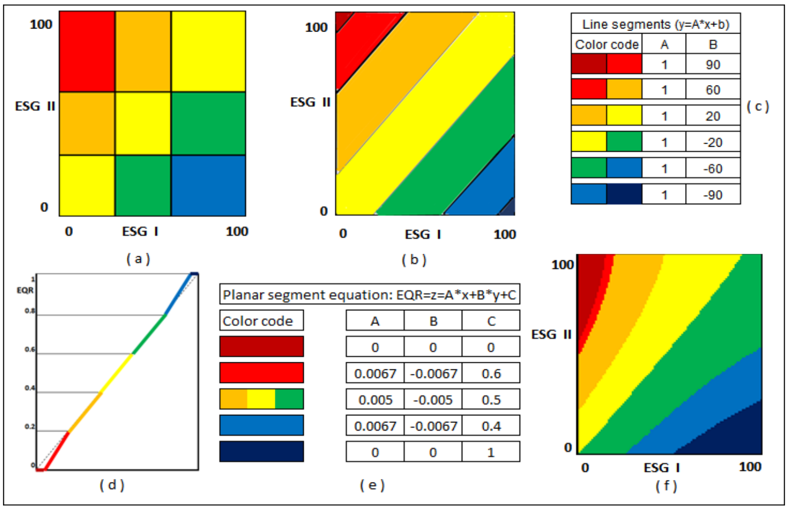
Planar Segments (Horizontal & Inclines) EQR=z=A*x+B*y+C			
Color code	A	B	C
	0.025	0	0
🟥	0	0	0.1
	0.025	-0.0025	-0.05
🟧	0	0	0.3
	0.025	-0.005	-0.1
🟨	0	0	0.5
	0.025	-0.0125	-0.15
🟩	0	0	0.7
	0.025	-0.03	-0.2
🟦	0	0	0.9
	0.025	-0.05	-1.25
⬛	0	0	1.0

(f)

Example: x = ESG I = 50, y = ESG II = 85.
The y-coordinate indicates that point (50, 85) is located on the reference-domain between the projections of Intersection Lines ⬜🟨 (5*50-120=130>85) and 🟨⬜ (2*50-52=48<85). Point (50, 85) is projected on the composite surface in segment 🟨 with z = EQR = 0.5.

(g)

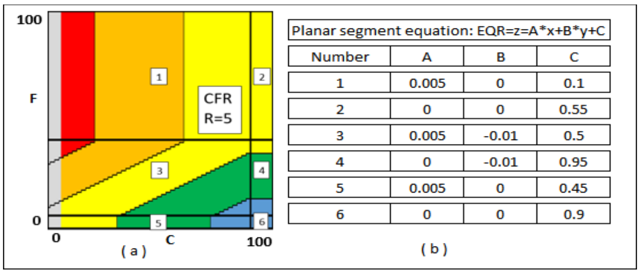
Figure 1. Elements of the RPI approach (color codes as per WFD; Figure parts described in text)



Line segments (y=A*x+b)		
Color code	A	B
🟫🟥	1	90
🟥🟧	1	60
🟧🟨	1	20
🟨🟩	1	-20
🟩🟦	1	-60
🟦⬛	1	-90

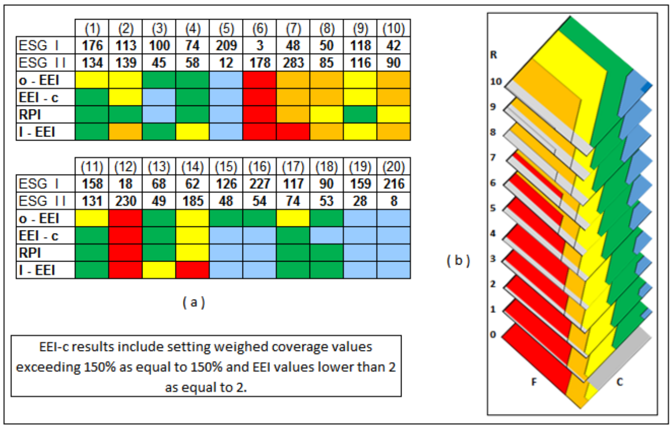
Planar segment equation: EQR=z=A*x+B*y+C			
Color code	A	B	C
🟫	0	0	0
🟥	0.0067	-0.0067	0.6
🟧🟨🟩	0.005	-0.005	0.5
🟦	0.0067	-0.0067	0.4
⬛	0	0	1

Figure 2. EEI model variants: (a) o-EEI; (b) to (e) l-EEI; (f) EEI-c (Figure parts described in text)



Planar segment equation: EQR=z=A*x+B*y+C			
Number	A	B	C
1	0.005	0	0.1
2	0	0	0.55
3	0.005	-0.01	0.5
4	0	-0.01	0.95
5	0.005	0	0.45
6	0	0	0.9

Figure 3. CFR model features for R=5 (Figure parts described in text)



	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
ESG I	176	113	100	74	209	3	48	50	118	42
ESG II	134	139	45	58	12	178	283	85	116	90
o - EEI	🟨	🟨	🟩	🟩	🟦	🟥	🟧	🟧	🟨	🟧
EEI - c	🟩	🟨	🟦	🟩	🟦	🟥	🟧	🟧	🟨	🟧
RPI	🟩	🟩	🟦	🟩	🟦	🟥	🟧	🟨	🟩	🟨
l - EEI	🟩	🟧	🟩	🟨	🟦	🟥	🟥	🟧	🟨	🟧

	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)
ESG I	158	18	68	62	126	227	117	90	159	216
ESG II	131	230	49	185	48	54	74	53	28	8
o - EEI	🟨	🟥	🟩	🟨	🟩	🟩	🟨	🟩	🟦	🟦
EEI - c	🟩	🟥	🟩	🟨	🟦	🟦	🟩	🟦	🟦	🟦
RPI	🟩	🟥	🟩	🟨	🟦	🟦	🟩	🟩	🟦	🟦
l - EEI	🟩	🟥	🟨	🟥	🟦	🟦	🟩	🟩	🟦	🟦

(a)

EEI-c results include setting weighed coverage values exceeding 150% as equal to 150% and EEI values lower than 2 as equal to 2.

Figure 4. Results: (a) ESC classification with o-EEI, EEI-c, RPI, l-EEI; (b) CFR model projections for R in [0, 10]

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