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A procedure to assess the relative merit of classification strategies for grouping environments to assist selection in plant breeding regional evaluation trials

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Abstract

Classification methodology is widely used by plant breeders to group environments on the results of regional evaluation trials to assist in selection among genotypes. To be effective, this strategy must be integrated with the theory of indirect selection. Environments which group together should reflect commonality of genotypic discrimination and therefore give rise to similar selection among genotypes. Four strategies for classifying environments were compared. These were based on untransformed and three forms of transformed data (coded, standardised and rank). The comparison assessed how effectively the groups of environments formed by using each transformation maximised the opportunity for exploiting indirect selection between environments within the same group relative to environments in other groups. The objective in this study was to identify groups of international environments, used by CIMMYT in its international nursery program, which gave high indirect response to selection for grain yield in six Australian environments. Generally the four classification strategies identified subsets of international environments for which selection gave a greater indirect response than that for selection on average performance across all of the international environments (35% to 94% on average over all Australian environments). Environmental classifications based on the standardised and rank transformations were generally superior to those based on the untransformed and coded transformations (46% on average over all Australian environments). The magnitude of this advantage differed between the Australian environments but was substantial for the two environments which expressed the greatest opportunity for exploiting indirect selection. These results have obvious and large implications for the use of classification methodology to structure regional testing regimes for plant breeding programs.

Key words: Breeding; Classification; Evaluation trial; Indirect selection; *Triticum*; Wheat

1. Introduction

Plant breeders have used various methods to group test environments on the results of plant breeding regional evaluation trials. This is commonly done to deal with the complicating influence of genotype by environment interaction when selecting among genotypes (Horner and Frey, 1957; Abou-el-Fittouh et al., 1969; Byth et al., 1976; Brennan et al., 1981; Fox and Rosielle, 1982a,b; Crossa et al., 1991; Heuhn, 1990; Ivory et al., 1992; Cooper et al., 1993b). A classification method commonly used is the agglomerative hierarchical procedure (Williams, 1976) with squared Euclidean distance (Burr, 1968) as a dissimilarity

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measure and incremental sum of squares (Ward, 1963; Burr, 1968, 1970; Wishart, 1969) as a grouping strategy. This procedure has been used in combination with a range of data transformations. The use of alternative data transformations with one grouping procedure generally results in different groupings of the genotypes or environments when applied to the same data set. The inability of a classification procedure to provide a definitive grouping of environments or genotypes has been noted (Westcott, 1986). The identification of the "best" grouping from a range of alternatives requires clear definition of the objective of grouping the environments.

A primary objective in considering relationships among environments in plant breeding experiments is the identification of the degree of commonality among the environments in the pattern of discrimination among the genotypes expressed in the environments. This can be used to assist characterisation of environments for the purposes of selection among genotypes, and as a consequence identify a reduced testing regime. When classification is used to group environments there is an implicit assumption that selection within any one environment will result in greater correlated response in those environments with which it groups, relative to those with which it does not group. Where alternative classification strategies give rise to different environmental groupings, these strategies must also reflect differences in the effectiveness of environment groups for use in exploiting indirect selection. The relative merit of four classification strategies for directing exploitation of indirect selection was more explicitly considered at the theoretical level by DeLacy and Cooper (1990) and their considerations were implemented by Cooper et al. (1993b).

DeLacy and Cooper (1990) suggested that transformation of the original data by coding, standardisation for phenotypic variation within environments (Fox and Rosielle, 1982b), and finally by conversion to genotypic ranks within environments, may be viewed as a process of progressively focussing the study of environmental relationships onto the information on genotypic discrimination which is relevant for assessing potential for exploitation of indirect selection between environments. Cooper et al. (1993b) used standardisation within environments to inter-relate the proximity measure squared Euclidean distance and the prediction formulae (Falconer, 1952, 1989) for indirect response to selection. However, they did not consider the relative advantage of this transformation strategy over the alternative data transformations investigated by DeLacy and Cooper (1990). This paper uses the wheat grain yield data set of Cooper et al. (1993b) to document these relationships.

The data set of Cooper et al. (1993b) consists of the grain yield data on 40 wheat lines evaluated in 18 international tests conducted by CIMMYT and 6 Australian tests in the State of Queensland. The agglomerative hierarchical classification procedure is applied to the original data and three transformed forms (coded, standardised and rank data) to jointly group the international and Australian environments. A graphical method is developed for comparing the relative merits of the four classification strategies.

In this study the alternative groupings are compared in relation to the specific objective of identifying subsets of the CIMMYT international tests which increase indirect response to selection in the Australian environments over that achieved for selection on average performance over all of the international environments. Specifically, a classification strategy is sought where the international environments are grouped with those Australian environments for which selection on international trial performance results in a high indirect response to selection in the Australian environment. Australian wheat breeders are particularly interested in exploiting indirect selection for grain yield performance in Australia on the results of CIMMYT trial data (Cooper et al., 1993a) because of the value of the CIMMYT germplasm to genetic improvement of wheat in Australia (Brennan, 1986) and the 2- to 3-year time lag between availability of international trial data and the initial evaluation of these lines in Australia due to strict quarantine regulations.

2. Materials and methods

Data sets

The details of the international and Australian data sets were described by Cooper et al. (1993a). The international data set was a subset of the grain yield results of the 17th International Bread Wheat Screening Nursery (IBWSN) which consisted of grain yield measured on 40 white-grained, rust-resistant wheat lines (P.S. Brennan, pers. commun., 1986) in 18 international environments. The Australian data set consisted of grain yield measured on the same 40 wheat lines, evaluated in six Australian environments consisting of an irrigated and rainfed treatment at three locations in Queensland. Significant line variation and line by environment interaction were identified for grain yield in both the international and Australian data sets (Cooper et al., 1993a).

The potential for exploiting indirect selection for grain yield in the six Australian environments from the results of the 17th IBWSN has been well characterised (Cooper et al., 1993a). In summary, the two high-yielding environments Gatton irrigated (GI) and dryland (GD) had high potential, the high- and intermediate-yielding environments Brookstead irrigated (BI) and Cecil Plains dryland (CD), respectively, had intermediate potential and the intermediate- and low-yielding environments Cecil Plains irrigated (CI) and Brookstead dryland (BD), respectively, had low potential.

Data transformation

Following DeLacy and Cooper (1990), line grain yield performance for the classification study was considered in terms of the deterministic linear model

$$p_{ij} = m + l_i + e_j + (le)_{ij}, \qquad (1)$$

where p_{ij} is the phenotypic performance of line i in environment j; m the grand mean, l_i the main-effect of line i over the j environments; e_j the main-effect of environment j over the i lines; and $(le)_{ij}$ the line by environment interaction effect of line i in environment j.

The grain yield data within each environment were subjected to three transformations; coded, standardised and rank data, following DeLacy and Cooper (1990). The coded transformation was achieved by subtracting the environment main-effect from each line value within that environment; the standardised transformation by dividing the coded line values within each environment by the standard deviation of the phenotypic variation within that environment; and the rank transformation by ranking the lines for relative grain yield from 1 to 40, substituting the rank value of the line for its grain yield value and dividing the rank values by the standard deviation of the variation among the ranks. The four grain yield data sets, one original and three transformed, for the 40 lines in each of the international and Australian environments were separately subjected to joint classification of the environments following Cooper et al. (1993b). The associations of the Australian and international environments arising from the four classifications were investigated.

Classification of environments

The environments were classified by the preferred (DeLacy, 1981; Ivory et al., 1992) agglomerative hierarchical procedure with squared Euclidean distance as the dissimilarity measure (Burr, 1968) and incremental sum of squares as the grouping strategy (Ward, 1963; Burr, 1968, 1970; Wishart, 1969). The use of squared Euclidean distance with each of the four transformations represented classification strategies which characterised environmental relationships in terms of four different aspects of line discrimination (DeLacy and Cooper, 1990); namely: for untransformed data, both the environment main-effects and the line by environment interaction effects $(e_j + (le)_{ij})$; for coded data, only the line by environment interaction effects $((le)_{ij})$; for standardised data, the phenotypic correlation between environments for relative line performance; and for rank data, the rank correlation between environments for relative line performance.

Measurement of indirect response to selection

Each classification strategy was assessed on the magnitude of indirect response in the Australian environments as a result of selection on line performance in the groups of international environments. Indirect response to selection was predicted using the formulae given by Falconer (1952, 1989), and was applied to the joint grouping of Australian and international environments derived by classification, as outlined by Cooper et al. (1993b). Selection was based on average line performance over the group of international environments identified by classification to group with each Australian environment, and response was evaluated in the appropriate Australian environment.

To further quantify the partitioning of Australian and international environments into classification groups in terms of indirect selection, indirect response was calculated for each Australian environment based on selection for line mean grain yield across both the subsets of international environments with which the Australian environments did and did not group. At each fusion point in the classification hierarchy, the international environments were considered to belong to one of two categories for each Australian environment; namely, those with which the Australian environment grouped (group category) and those with which it did not (non-group category).

The determination of the group and non-group categories of international environments is demonstrated for the Australian environment Brookstead irrigated (BI) (Fig. 1). At the five-group truncation level, BI and another Australian environment (CD) are in group 43 with six international environments. These six international environments comprise the group category at this truncation level. The remaining 12 international environments comprise the non-group category for BI. At the four-group level, groups 38 and 43 from the five-group level fused to form group 44, and BI is now grouped with seven international environments. The international environment Pirsabak which was in the non-group category for BI at the five-group truncation is in the group category for BI at the four-group truncation. Therefore, the composition of the group and non-group categories changed for BI between the five- and four-group truncation levels. By contrast, the composition of the group and non-group categories did not change for BI between the four- and three-group levels (Fig. 1).

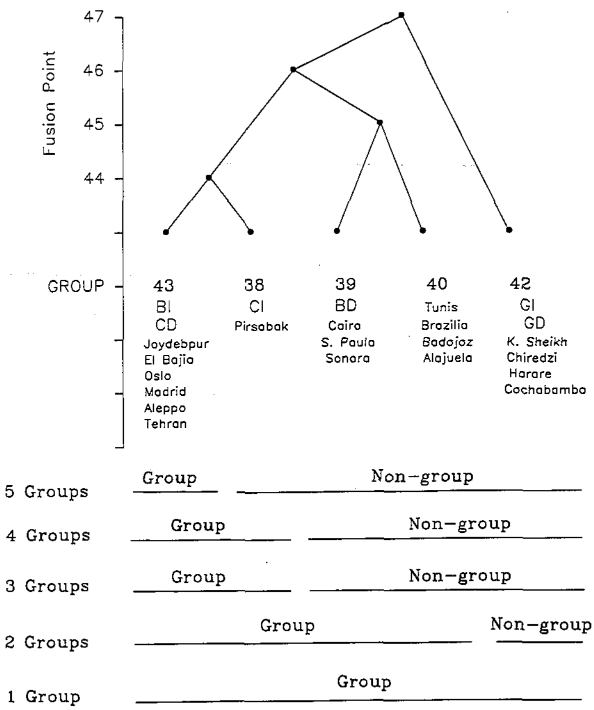

Fig. 1. Determination of the environmental composition of the group and non-group categories of international environments for the Australian environment Brookstead irrigated (BI) based on the standardised classification strategy.

The composition of the group and non-group categories of international environments was determined in this way for each Australian environment at each truncation level in the hierarchy. For each classification strategy, indirect response to selection for each Australian environment was predicted for selection based on average line performance across the international environments comprising the group and non-group categories of international environments at each truncation level in the hierarchy. The predicted indirect response to selection for both the group and non-group categories was plotted against the number of environment groups at each fusion point of the hierarchy to give a graphical representation of the effectiveness of selection. These graphical representations of the response to indirect selection (referred to as indirect response-profiles) were produced for each Australian environment. The effectiveness of the four classification strategies was assessed by comparing these indirect response-profiles.

If the classification groups Australian environments with those international environments which provide the most similar discrimination among the lines, selection on average line performance for the group category will result in greater indirect response to selection in the Australian environment than for that based on the non-group category. Further, for classification to be of value in this context, the response to indirect selection based on the group category must be greater than that based on average performance over all international environments.

Therefore, three comparisons were used:

1. The relative effectiveness of the classification strategies was assessed by comparing the indirect response to group category selection in each Australian environment at each fusion point.
2. The indirect response to selection for the group category was compared with that for selection on average performance over all international environments.

3. The indirect responses to selection for the group and non-group categories of international environments were compared in each Australian environment at each fusion point.

Two reference points were used for interpretation of these comparisons; namely, zero indirect response to selection (equivalent to random sampling of lines for the Australian environment) and indirect response to

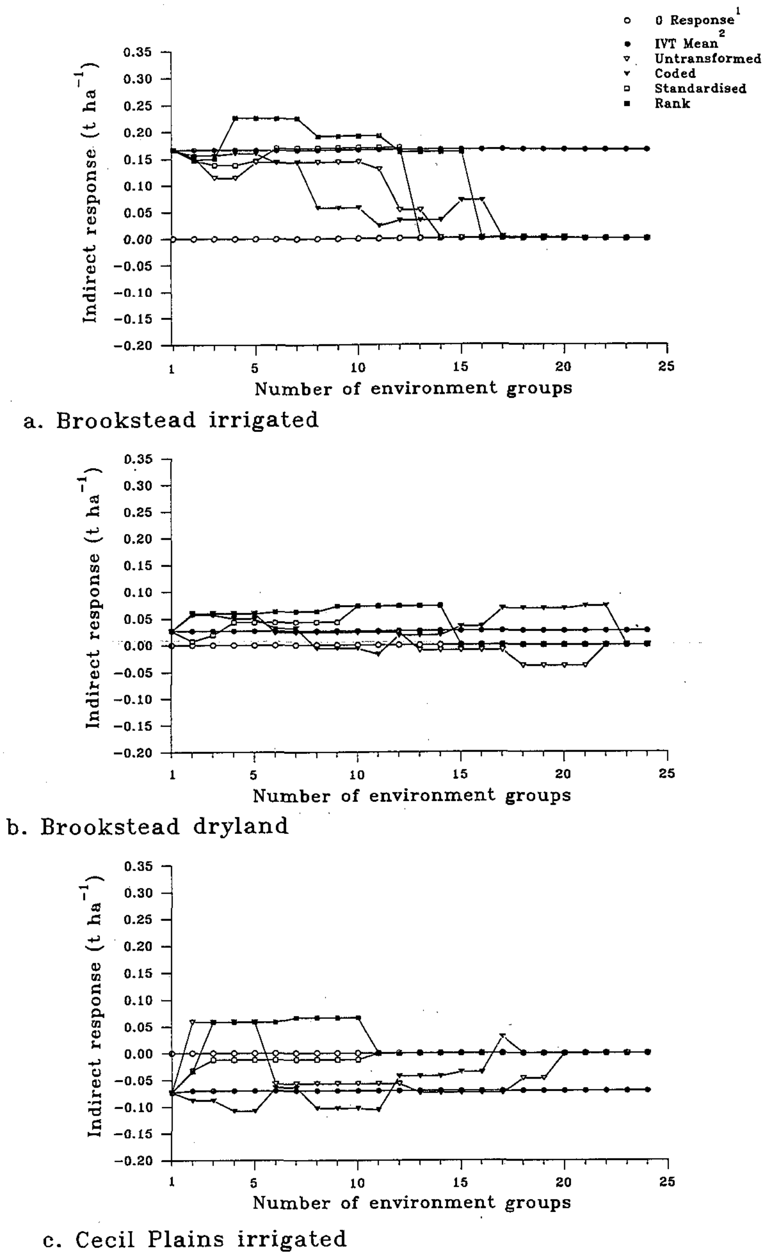

Fig. 2. Indirect response to selection for grain yield in six Australian environments for selection on average grain yield over the international environments comprising the group category at each truncation level of the joint classification of 6 Australian and 18 international environments based on the untransformed, coded, standardised and rank data. [1] 0 Response is the expected indirect response if no selection is applied and a random sample of lines are evaluated in the Australian environments. [2] IVT Mean is the predicted indirect response to selection in the Australian environment for selection based on average line grain yield over the 18 international environments.

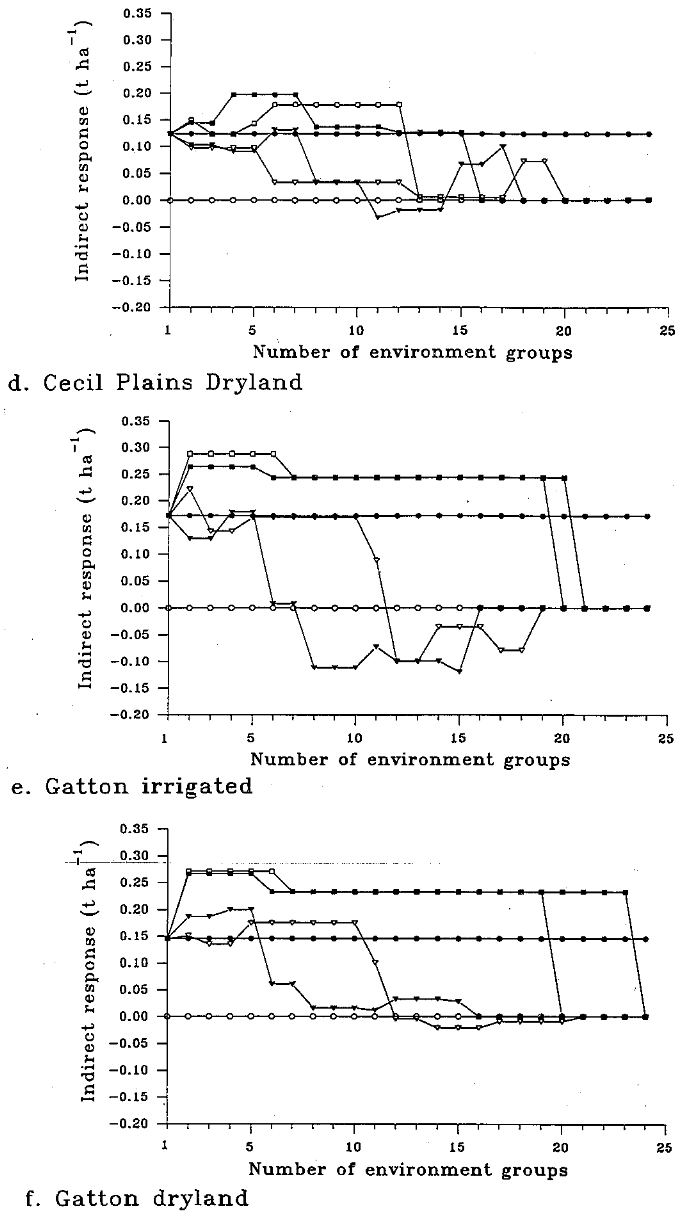

Fig. 2. continued.

selection on average performance over all international environments.

The indirect response-profiles provide a graphical representation of the relative magnitude of indirect response to selection within the Australian environments for the whole hierarchy. Prior to classification (24-group level in this study) there is no association by classification of the Australian and international environments, so that the indirect response will be zero for the group category and equal to selection on average performance over all international environments for the non-group category. By contrast at the one-group level of the classification, indirect response for the group category will be equal to selection on average performance over all international environments, and must be zero for the non-group category. Between these extremes, the response surface for indirect response to selection for the group and non-group categories will be determined by the way in which the Australian environments group with the international environments.

3. Results

Comparison of indirect responses to selection on the group category

The differences among the hierarchical associations of the international and Australian environments for the four classification strategies are reflected in different indirect responses to selection within the Australian environments for selection on grain yield performance for the group category of international environments (Figs. 2a to f). For each Australian environment, the standardised and rank classification strategies resulted in greater indirect response than for the raw and coded classifications. The magnitude of the advantage was greatest for both Gatton environments (Figs. 2e and f), intermediate for Brookstead irrigated (Fig. 2a) and Cecil Plains dryland (Fig. 2d), and least at Brookstead dryland (Fig. 2b) and Cecil Plains irrigated (Fig. 2c). This reflected the previously determined potential for exploiting indirect selection for grain yield for the six Australian environments (Cooper et al., 1993a).

For each Australian environment, the maximum indirect response to group category selection was positive and generally greater than that for selection based on average performance over all international environments (Table 1). This was more consistently achieved using the standardised and rank classification strategies (Figs. 2a to f). At some truncation levels the untransformed and coded classification strategies were also effective, but the incidence of this was more erratic and generally the magnitude of the response was less than that achieved by the standardised and rank classification strategies. On average over the six Australian environments, each classification strategy gave a greater indirect response to selection than that for selection on average performance over all of the international environments (Table 2). The untransformed and coded strategies both gave a similar advantage with the standardised and rank strategies giving a further 46% advantage on average over the six Australian environments. Therefore, the standardised and rank classification strategies were considered to be the most effective in allocating Australian environments with sub-sets of the international environments which provided scope for enhancing the indirect response to selection.

The maximum indirect response from classification on the rank transformation was substantially greater than that for standardised data in the two environments Brookstead irrigated and Cecil Plains irrigated (Table 1) and the strategies were essentially equal in effectiveness for the other environments.

Table 1
Maximum indirect response to selection for grain yield ($t\,ha^{-1}$) in six Australian environments for selection on the group category of international environments from joint classification on untransformed, coded, standardised and rank data and for indirect response for selection on average performance across all of the international environments

Classification strategy	Environment[b]					
	Brookstead I	Brookstead D	Cecil Plains I	Cecil Plains D	Gatton I	Gatton D
Untransformed	0.152	0.060[a]	0.059[a]	0.097	0.221[a]	0.175[a]
Coded	0.160	0.073[a]	0.031[a]	0.131[a]	0.179[a]	0.200[a]
Standardised	0.170[a]	0.073[a]	−0.012[a]	0.178[a]	0.288[a]	0.271[a]
Rank	0.226[a]	0.073[a]	0.067[a]	0.197[a]	0.264[a]	0.267[a]
Average IVT	0.166	0.027	−0.073	0.124	0.172	0.146

[a]Group indirect response to selection greater than that for average performance across all of the internatonial environments.
[b]For the Australian environments I and D are the irrigated and dryland treatments, respectively.

Table 2
Average advantage over 6 Australian environments of maximum indirect response to selection for grain yield from selection on the group category of international environments identified by joint classification on untransformed, coded, standardised and rank classification strategies in comparison to indirect response to selection for average performance across all of the international environments

Classification strategy	Average indirect response over 6 Australian environments ($t\ ha^{-1}$)	Percentage advantage over average IVT (%)	
		Individual classification strategies	Grouped classification strategies[a]
Untransformed	0.127	35	36
Coded	0.129	37	
Standardised	0.161	71	82
Rank	0.182	94	
Average IVT	0.094		

[a]The classification strategies were considered jointly in two groups: i. untransformed and coded; and ii. standardised and rank.

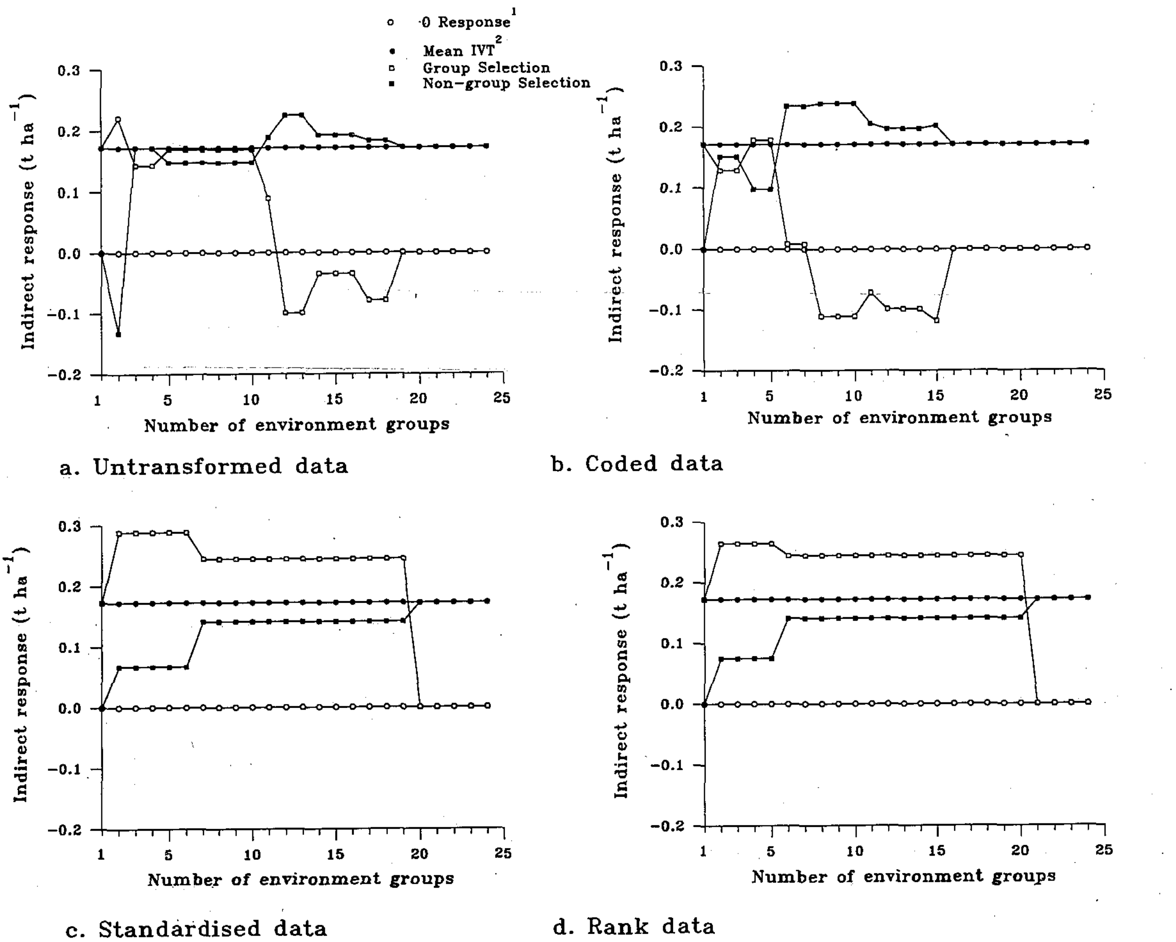

Fig. 3. Indirect response to selection for grain yield at Gatton irrigated for selection on average grain yield over the international environments comprising the group and non-group categories at each truncation level of the joint classification of 6 Australian and 18 international environments based on the untransformed, coded, standardised and rank data. [1,2] See notes to caption to Fig. 2.

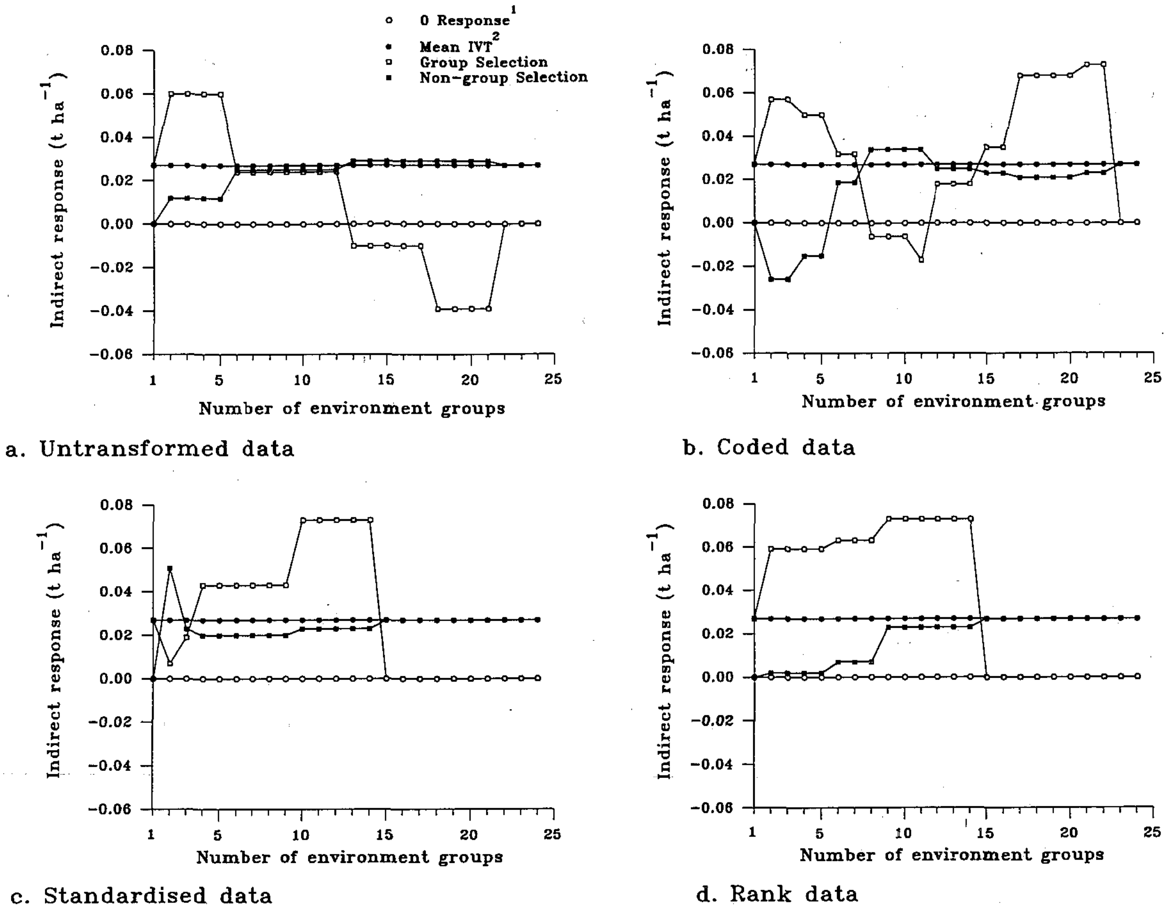

Fig. 4. Indirect response to selection for grain yield at Brookstead dryland for selection on average grain yield over the international environments comprising the group and non-group categories at each truncation level of the joint classification of 6 Australian and 18 international environments based on the untransformed, coded, standardised and rank data. [1,2] See notes to caption to Fig. 2.

Comparison of group and non-group selection categories

The relative magnitude of indirect response for group and non-group selection differed for each classification strategy and with the fusion level considered within the hierarchy. Therefore, assessment of the effectiveness of the classification strategies for grouping Australian environments with the international environments required consideration of the indirect selection response-profile for the whole hierarchy. The responses for only two of the Australian environments will be considered; the high-yielding Gatton irrigated trial (Figs. 3a to d) for which there was high potential to exploit indirect selection and the low-yielding Brookstead dryland trial (Figs. 4a to d) for which there was limited potential to exploit indirect selection.

At Gatton irrigated, non-group selection gave a greater indirect response than group selection for both the untransformed and coded classifications (Figs. 3a and b). Generally, indirect response for group selection at high group numbers was negative and increased with decreasing group numbers. Therefore, the untransformed and coded classifications did not group Gatton irrigated with those international environments which allowed the greatest exploitation of indirect response to selection for this environment. However, for both the standardised (Fig. 3c) and rank (Fig. 3d) classifications, indirect response based on group selection was greater than for non-group selection and for average performance across all international environments.

At Brookstead dryland, both the magnitude of indirect response to selection and the distinction between the untransformed or coded transformations and the standardised or rank transformed classifications were less than for Gatton irrigated (Fig. 4). While selection on the group category for the untransformed and coded classifications resulted in indirect responses greater than those for average performance across all the international environments at some fusion points (Figs. 4a and b), the responses were erratic. The results suggested that Brookstead dryland was inconsistently grouped by these classifications with environments with potential to provide indirect response to selection. By contrast, selection using both standardised (Fig. 4c) and rank (Fig. 4d) classification strategies resulted in a more consistent indirect response to selection, with group selection providing a greater response than for non-group selection. This was most evident for the rank classification.

4. Discussion

Many analytical techniques are available to the plant breeder for investigating the results of regional evaluation trials. In many cases the choice of which technique to use is based on heuristic grounds after empirical evaluation of a range of methods or on what method is readily available in accessible computer packages. Identification of appropriate analytical techniques is enhanced where the application of the techniques is considered in context with plant breeding objectives and a method is available for assessing the effectiveness of the techniques in achieving these objectives.

In this study, consideration of the application of classification to the grouping of environments in terms of indirect selection provided a basis for assessing which of the four classification strategies considered was "better". Quantifying indirect response to selection achieved by the classification strategies through the group indirect selection response-profiles provided a means of assessing the relative merit of the strategies.

These response-profiles provided an effective graphical display of the relative merits of the four classification strategies. Further, the group indirect selection response-profile provides an effective framework for assessing the effectiveness of additional classification strategies not considered here. The whole response-profile should be considered when comparing alternative classification strategies as conclusions drawn on a specified truncation level are conditional on the truncation level and provide only a limited assessment of the relative merit of the strategies.

The standardised and rank classification strategies were generally more effective than the untransformed and coded strategies in grouping Australian environments with a subset of international environments which offered potential to exploit indirect selection for those Australian environments. Both of the former strategies identified groups of international environments which gave a greater indirect response to selection than the non-group category and that for selection on average performance across all international environments.

The lower effectiveness of the untransformed and coded classifications was evident by the greater indirect response to selection for the non-group category relative to the group category of selection environments. This paradoxical result can be understood by considering the aspects of the differences among environments which are emphasised when the dissimilarity measure squared Euclidean distance is applied to the different forms of transformed data. Neither the untransformed or coded data explicitly emphasise relationships between environments which are associated with the opportunity to exploit indirect response to selection between the environments (DeLacy and Cooper, 1990). Classification based on untransformed data generally produces groups of environments with similar mean attribute level (Ivory et al., 1992). Where coded data are used, heterogeneity of variance among environments has a large influence on grouping of environments.

However, transformation of data by standardisation or conversion to ranks focuses the comparisons of environments onto aspects of discrimination among genotypes, the phenotypic and rank correlation between environments respectively, which are relevant for exploiting indirect selection between environments. From theoretical arguments, the standardisation transformation directly relates the grouping of environments to the genetic correlation underlying indirect selection (Cooper et al., 1993b).

The slight advantage of the rank over the standardised strategy in two of the six Australian environments considered in this study suggests that grouping of environments on ranks may be worth further consideration. However, for the two environments identified by Cooper et al. (1993a) to show the highest potential for exploiting indirect response to selection, Gatton irrigated and dryland, the standardised and rank transformations were equally effective in identifying subsets of international environments which gave a high indirect response to selection.

Classification of the international and Australian environments should be viewed as an exploratory analysis. When interpreting the groupings two questions are of importance. The first, intrinsic to the data set, is; can the classification strategy identify environmental relationships which reflect the scope for exploiting indirect selection? This is the question the present study considered. The second question, extrinsic to the data set used in the analysis, is; how repeatable are the grouping associations between the international and Australian environments?

If a classification strategy is to be of value for assisting indirect selection, it must group the international and Australian environments in a way which reflects the scope to exploit indirect selection, if such opportunities exist. This was achieved by the standardisation and rank classification strategies but not the untransformed or coded classifications. Therefore, the environmental grouping derived by the standardised and rank classification strategies should be viewed as an effective summarisation of the relationships between the international and Australian environments, where the focus is to explore the opportunity for exploiting indirect selection. This analysis is retrospective as it highlights relationships intrinsic to the data set subjected to classification analysis. The indirect response to selection predicted for the Australian environments from the joint grouping of the international and Australian environments can be tested in an independent set of the target Australian environments. The testing of such predictions is essential.

The repeatability of the environmental groupings will influence the realisation of the predicted indirect response to selection. The value of environmental relationships identified by classification will depend on whether those subset(s) of international environments identified as providing high indirect response in the intrinsic analysis can be used to predict indirect response in future years and for genotypes other than those used in the grouping analysis. This question should be addressed where classification is used to group environments or genotypes on data from multi-environment experiments. There is a need for studies which evaluate the consistency of groupings in independent data sets.

The principles considered in this study could be applied to other situations where the plant breeder has a well-defined selection and target population of environments. The objective is to identify which selection environments are useful for obtaining maximum indirect response in the target environments. The objective of selection in current trials is to maximise indirect response to selection for future environments into which the selected genotypes will be released for further testing or as cultivars. The current year's trials are the selection population of environments and the future environments are the target population of environments. The historical trials conducted by the plant breeder provide a sample from this target population of environments and could be used to identify those environments which can maximise correlated response to selection.

In most cases the judgements on the value of the test environments are made subjectively by the plant breeder. This process can be placed on a more quantitative foundation by using classification to group current plant breeding trials with historical trials as a basis for assessing the historical relevance of the current trials. To use joint classification to identify the appropriate selection environments in the current year's trials a set of genotypes must be common to both the selection and target environments. This can be achieved through inclusion of check lines from historical data sets to enable comparison of current breeding trials with historical trials, thus allowing an assessment of the historical relevance of specific trials which could be weighted accordingly. The problem associated with this procedure is the genotype-specific nature of the environmental comparisons. To improve this process, specific probe genotypes could be used as diagnostic sets (Cooper et al., 1990) to act as a bioassay of the conditions encountered in the plant breeding trials. Where this is effective the environmental characterisation provided by the probe genotypes will allow a direct assessment of the value of an environment for selection purposes.

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