A Simple Strategy for Identifying Conserved Features across Non-independent Omics Studies

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Abstract

False discovery is an ever-present concern in omics research, especially for burgeoning technologies with unvetted specificity of their biomolecular measurements, as such unknowns obscure the ability to characterize biologically informative features from studies performed with any single platform. Accordingly, performing replication studies of the same samples using different omics platforms is a viable strategy for identifying high-confidence molecular associations that are conserved across studies. However, an important caveat of replication studies that include the same samples is that they are inherently non-independent, leading to overestimation of conservation if studies are treated otherwise. Strategies for accounting for such inter-study dependencies have been proposed for meta-analysis methods that are devised to increase statistical power to detect molecular associations present in one-or-more studies but are not immediately suited for identifying conserved molecular associations across multiple studies. Here we present a unifying strategy for performing inter-study conservation analysis as an alternative to meta-analysis strategies for aggregating summary statistical results of shared features across complementary studies, while accounting for inter-study dependency. This method, which we refer to as "adjusted maximum p-value" (AdjMaxP), is easy to implement with both inter-study dependency and conservation estimated directly from the p-values from molecular feature-level association testing results from each study. Through simulation-based assessment we demonstrate that AdjMaxP's improved performance for accurately identifying conserved features over a related meta-analysis strategy for non-independent studies.

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Introduction

Omics assaying technologies are continuously advancing the types of biomolecules that can be profiled at high-throughput scale. However, a caveat to these burgeoning technologies is that their reliability may be unvetted and "gold standard" have yet to be established, particularly in terms of the specificity their molecular capture and susceptibility to technical artifacts. False discovery has been an ever-present concern in omics research, such that it is commonplace for potential discoveries of omics research to undergo additional validation, generally by being supported by analysis of independent omics data or by targeted in-vivo experiments. Proteomics is one such omics domain for which multiple novel platforms have been recently developed, promising improved throughput, replicability, and efficiency for

measuring protein abundance compared to liquid chromatography tandem mass spectrometry, which has been the dominant platform [1]. Emerging technologies include SomaScan [2] and Olink platforms, which are currently designed to measure the abundance of ~7,000 and ~3,000 human proteins, respectively. However, the specificity of their respective protein capture is unclear and studies have reported a lack of concordance between these platforms [3,4]. Accordingly, these unknowns obscure the ability to characterize biologically informative features from studies performed with any single platform.

Performing replication studies of the same samples using different omics platforms is a strategy for identifying high-confidence molecular associations. This approach that we refer to as **inter-study conservation** prioritizes associations that demonstrate statistical significance across studies. For this approach, the simplest strategy is to perform independent analyses across studies, and establish conserved associations based on shared statistical significance. However, this strategy is prone to loss of sensitivity, especially for omics studies in which multiple hypothesis correction procedures are generally warranted. In contrast, meta-analyses generally seek to increase the sensitivity of feature discovery by aggregating statistical results across complementary studies without requiring that associations reach statistical significance within each study. While this approach gains statistical power, it is susceptible to spurious findings driven by artifacts of any one study, especially without post-analytical consideration.

An important caveat of replication studies that include the same samples is that they are inherently non-independent. In this context, inter-study conservation needs to address the statistical dependency of the results derived from the analysis of the same samples using different technologies. Otherwise, treating the studies as independent overestimates the number of effective number of studies performed, leading to inflation of type 1 error. Province and Borecki [5], proposed a strategy for accounted for inter-study dependencies based on the correlation between statistical results across studies. This strategy makes use of the assumption that for omics studies, most statistical results follow arise from the null hypothesis, thus the correlation between inter-study results captures the degree of their statistical dependency. However, Province and Borecki [5] implement of this strategy as an adaptation of Stouffer's Z-score meta-analysis method [6], and thus suffers from the complications for establishing inter-study conservation.

Here we present a simple statistical method for performing inter-study conservation analysis as an alternative to meta-analysis strategies for aggregating summary statistical results of shared features across complementary studies. For accounting for inter-study dependency, our study our strategy adapts that of Province and Borecki [5]. Thus, our method functions as a complementary strategy for aggregating summary statistical results across studies that reduces the influence of artifacts in any one study, and thereby reducing the potential for reporting of spurious findings.

Methods

Identifying conserved statistical associations for shared features across correlated data sets

Our approach, which will refer to here as **"adjusted maximum p-value" (AdjMaxP),** is a

strategy for aggregating inter-study statistical testing results to identify features for which evidence of statistical association is conserved, while accounting for inter-study dependency arising from shared subjects. AdjMaxP is performed using vectors of nominal p-values calculated from feature-level, e.g., gene-level and protein-level, association testing results from individual studies, and aggregates multiple results for each shared feature to a single p-value. This approach offers a major advantage over the common "naïve" approach of assigning conservation based on shared statistical significance across studies. Accordingly, high-confidence features of can be identified, even for instances where statistical significance criteria are not met by either study. Moreover, by accounting for inter-study dependency, our approach we control the type 1 error rate, otherwise inflated when assuming independence.

AdjMaxP builds on the maximum p-value test proposed by Wilkinson[7]. Suppose we have N studies, each reporting association p-values $(p_{i1} \dots p_{iK})$ for K omics features. We assume that the results from the N studies are correlated, for example if samples from the same subjects are used with different technology. Wilkinson's maximum p-value test calculates an aggregate p-value, P_{agg}, for each feature k directly as:

$$P_{agg,k} = P_{max,k}^{N}$$

where

$$P_{max,k}^{N} = (max_i(p_{ik}))^N.$$

Intuitively, if the maximum p-value is small, we can reasonably infer consistent association across all studies, and thus conclude validity of the result. However, $P_{agg,k}$, assumes independence across the N studies, but if the results are correlated the type 1 error rate can be inflated. We devised the AdjMaxP to better control the type 1 error rate with correlated studies. The intuition of the method is that if study results are correlated, then the **"effective number of studies" (ENS)** is smaller than N. In the extreme case of perfect inter-study dependence, in which each of the N p-values p_{ik}must be equal then ENS is equal to 1. The opposite situation is when the studies are completely independent, so that ENS=N. In general

$$1 \leq \text{ENS} \leq \text{N}$$

and an estimate of the aggregate p-value P_{agg}^{*} that is inter-study dependency corrected is given by

$$P_{agg}^{*} = P_{max}^{ENS}.$$

To determine an adequate estimate of ENS, we adapted the modification of Stouffer's Z-score-based meta-analyses of large-scale omics studies introduced by Province and Borecki [5] to account for inter-study dependence. For each feature k, Stouffer's Z-score aggregates the study specific z-scores

$$Z_{agg,k} = \sum_{i=1}^{N} Z_{ik},$$

where, $Z_{agg,k}$, follows a normal distribution, $N(0, N)$ under the null hypothesis. When the study results are correlated, Province and Borecki demonstrated that $Z_{agg,k}$, follows a normal distribution, $N(0, V)$ with $N \leq V < N^2$, and V is calculated by summing all values of the N by N matrix of pairwise inter-study correlation,

$$V = sum(\Sigma).$$

For "omics" studies, they propose estimating Σ directly from the N vectors of study-specific z-scores that are calculated as the compliment probit transformation of the p-values, and Σ is estimated using tetrachoric correlation after transforming z-score values into two categories defined by z > 0 and z < 0. As justification for tetrachoric correlation over Pearson correlation, they argue that for feature-by-feature hypothesis testing of omics data sets, most statistical tests follow the null distribution, such that features under the alternative hypothesis inflate estimation of the inter-study dependency if measured by Pearson correlation, leading to reduced statistical power. Under this assumption tetrachoric correlation is preferrable because it dampens the leverage of these features.

To estimate ENS, we implement a method, first proposed by Li et al [8,9], which utilizes the eigenvalues, λ_i, following eigen-decomposition of Σ , and is calculated by

$$ENS = N - \sum_{i=1}^{N} [I(\lambda_i > 1)(\lambda_i - 1)].$$

Under inter-study independence, all eigenvalues are equal to 1, yielding an ENS = N, and under complete inter-study dependence, $\lambda_1 = N$, yielding an ENS = 1, satisfying 1 ≥ ENS ≥ N.

Simulation-based evaluation of validation method

To assess the performance of AdjMaxP for identifying conserved statistical associations under inter-study dependence, we performed a simulation study by repeatedly simulating N correlated sets of K z-scores. In these simulations, the z-scores represent compliment probit transformation of p-values from study-specific significance tests.

For each simulation, we generated subsets of the K features under the null hypothesis of no association S_n, an unconserved subset S_u of features that were significant in only one study, and a conserved subset S_c of shared true positives across the N studies. Each simulation was initialized by simulating P = 10,000 sets of z-scores from a multivariate normal distribution with mean = 0 and covariance given by an N-dimensional correlation matrix, where off-diagonal correlation values represent the background level of inter-study dependence. Unconserved and conserved subsets of features, S_u and S_c, were simulated by adding a signal value, S, to initialized z-scores. For S_u features, signal was added to between 1 and N-1 studies and for S_c features, signal was added to all N studies. The evaluate the performance under different conditions, the simulated data sets were generated under different combinations of parameters. These parameters number of studies, N, the inter-study background correlation

level, C, the level of signal, S, added to either S_u and S_c features, and the proportion of the total features, Pr, represented by either S_u and Sc. The specific values of these evaluated included

- N: 2, 3
- C: 0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0
- S: 0, 2, 4
- Pr: 0.0, 0.2.

Simulations based on each combination of parameters was performed 25 times.

For comparison, we evaluated both AdjMaxP and the Province and Borecki method. For each simulation, we applied these methods and calculated a series of performance metrics based on the discovery of Sc features at both nominal p-value and Benjamini-Hochberg false discovery rate (FDR) corrected q-value [10] thresholding. Finally, model performance was evaluated based on five measures, specificity, sensitivity, precision, and area-under-the-curve (AUC).

Results

To evaluate the relative performance of AdjMaxP and the Province-Borecki method for identifying features for which statistical associations are conserved across studies under inter-study dependency, we ran these methods on simulated test results representing varying levels of inter-study dependency, and unconserved and conserved statistical association. The distributions of performance estimations demonstrated little variability across replicate simulations of the same conditions. Mean performance estimates across all metrics and conditions evaluated are reported in Supplemental Table S1 and Supplemental Table S2 for two- and three-study simulations, respectively.

We first assessed the specificity of these methods in simulations in which no features are conserved, based on a nominal p-value threshold of 0.05, Under this condition, if no unconserved features were present in the data both methods performed similarly, and consistently yielded specificity estimates near the expected, 0.95, across all background correlation levels (Figure 1 Ai, Bi). However, for simulations with 20% unconserved features, the performance of the two methods diverged with AdjMaxP consistently yielding higher specificity across all background correlation levels (Figure Aii-iii, Figure Bii-iii). Moreover, trends of AdjMaxP were consistent across different magnitudes of unconserved signal, while Province-Borecki yielded markedly decreased specificity between signal magnitudes of 2 (Figure Aii, Bii) and 4 (Figure Aiii, Biii).

Next, given that in-practice feature discovery is generally performed based statistical significance thresholding, we evaluated the relative precision, specificity, and sensitivity of these methods based on FDR corrected q-value thresholding of 0.05. At this significance threshold, the precision of these methods diverged under 20% unconserved features and as the magnitude of unconserved signal increased with AdjMaxP outperforming Province-Borecki (Figure 2A, Supplemental Figure S1A). Notably, at high unconserved signal magnitude, the precision of Province-Borecki was especially low, yielding mean estimates ~0.55 for two-study and ranging between 0.60 and 0.50 for three-study simulations, while all mean precision estimates of AdjMaxP were greater than 0.85. (Figure 2Aiii, Supplemental Figure S1Aiii). Finally,

These trends in precision were related to those of sensitivity and specificity, and AdjMaxP generally yielded higher specificity and lower sensitivity compared to Province-Borecki (Figure 3B-C, Supplemental Figure S2B-C).

Finally, we evaluated the relative performance of these method across varying significance thresholds using AUC, as well as sensitivity given a set specificity threshold of 0.95. For either metric, the relative performance of AdjMaxP and Province-Borecki, varied based on the presence and magnitude of unconserved signal (Figure 3, Supplement Figure 2). If no unconserved features were present in the data, Province-Borecki generally outperformed AdjMaxP (Figure 3Ai, Bi, Supplemental Figure S2Ai, Bi). However, at 20% unconserved features of high signal magnitude, 4, AdjMaxP outperformed Province-Borecki (Figure 3Aiii, Biii, Supplemental Figure S2Aiii, Biii). Finally, at lower unconserved signal magnitude, 4, the the performance of the two methods were similar, and AdjMaxP outperformed Province-Borecki at higher levels of background correlation (Figure 3Aii, Bii, Supplemental Figure S3Aii, Bii). This difference in sensitivity between methods can be attributed to differences in the p-value threshold that yields 95% specificity. For AdjMaxP, at 20% unconserved features, the p-value required to achieve 95% specificity remains ~0.05, while for Province-Borecki this p-value threshold drops to below 0.005 for high unconserved signal (Figure 3Cii-iii, Supplemental Figure S2 Cii-iii).

Overall, AdjMaxP outperforms Province-Borecki under conditions in which unconserved features are present in the data across various metrics, and the level of divergence increased with the magnitude of unconserved signal., Moreover, trends in AdjMaxP performance estimates demonstrated minimal changes across varying magnitudes of unconserved signal. Finally, these trends were consistent across simulations of two- and three-studies.

Discussion

Our AdjMaxP method is a simple approach for identifying conserved statistical associations of shared features across omics studies under inter-study dependencies when unknown technical factors may limit the specificity of any one platform. Importantly, although for convenience we make the distinction between AdjMaxP and meta-analysis methods, AdjMaxP is similar to meta-analysis methods in that it is more sensitive than independently considering shared statistical significance across studies in order to establish conservation. Like Province-Borecki, AdjMaxP doesn't require that the full set of subjects are shared across platforms, nor does it require that the exact number of overlapping subjects is known [5].

Our simulations studies demonstrated that AdjMaxP should yield high precision under varying potential for technical artifacts in one-or-more studies. AdjMaxP consistently outperformed Province-Borecki for identifying conserved features, under high levels of unconserved signal across studies. The performance of AdjMaxP was relatively unaffected by changes in the level of unconserved signal, whereas the performance Province-Borecki was negatively affected by these changes. This is unsurprising, given that Province-Borecki is based on the sum of z-scores across studies, thus statistical significance can be reached from these tests if signal from only one study is high.

Finally, several additional considerations are relevant when applying AdjMaxP. Since AdjMaxP significance testing is a function of the maximum p-value of a given feature across

studies, we note that disproportionately higher weight if given to studies with less statistical power to detect true associations, either by greater noise and/or smaller sample size. However, this shortcoming is of no detriment to the overall precision but may negatively impact sensitivity for identifying these features. Additionally, spurious findings are possible if studies share features with technical artifacts, either by chance or by similar aspects of their molecular capture, e.g. multiple studies performed using similar sequencing or probe-based technologies. Thus, spurious findings will be most limited when studies are performed on disparate technologies.

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Figures

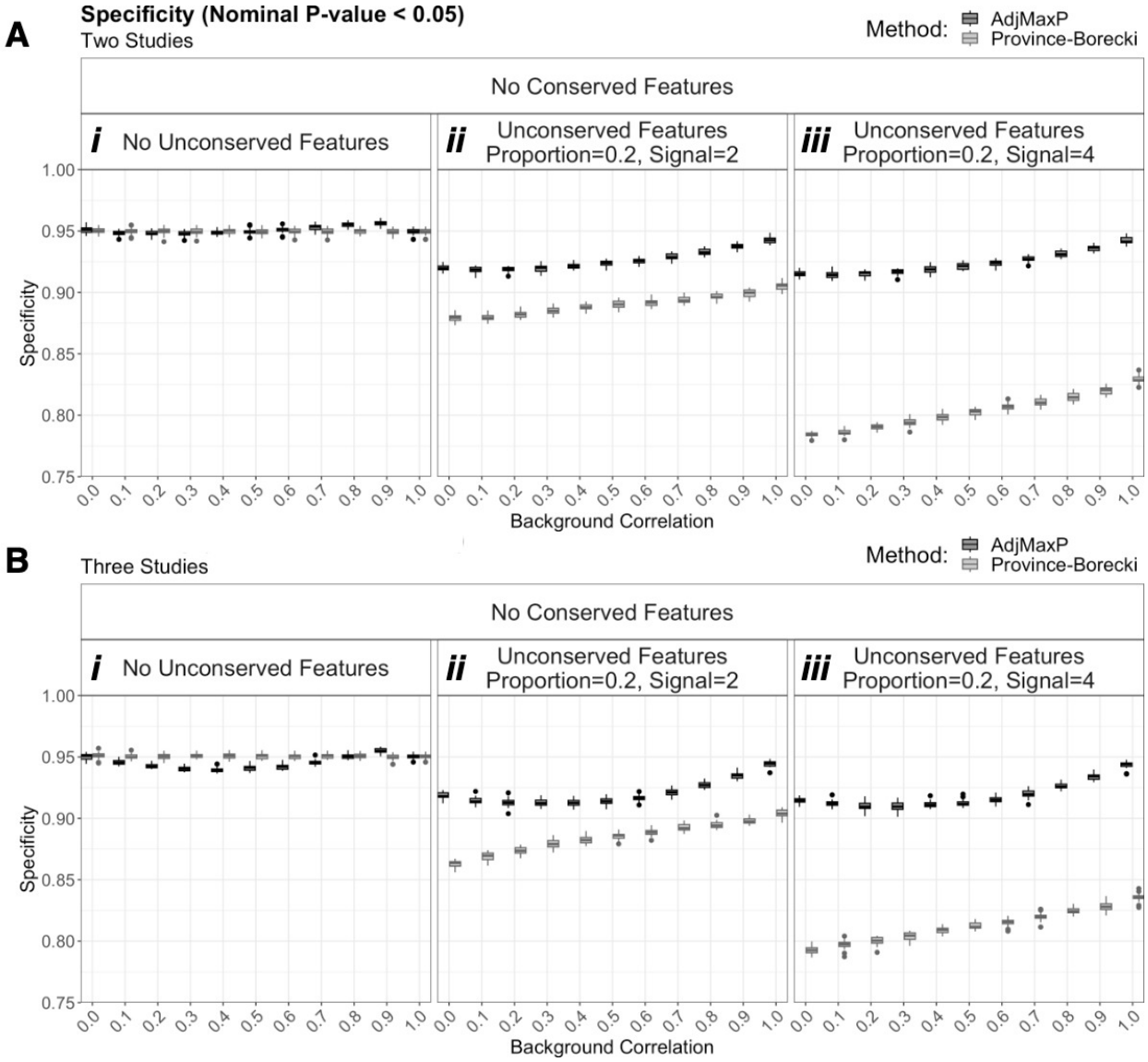

Figure 1: Comparison of specificity simulations of two and three studies with no conserved features, based on a nominal p-value thresholding of 0.05.

Boxplots reflect the distribution of specificity at p-value threshold, 0.05, for 25 simulations of 10,000 shared features at different levels of background correlation and unconserved signal, across simulations of two and three studies with no conserved features. “Conserved” and “Unconserved” features refer to features for which signal was added (i.e. deviate from the null distribution) across all studies or fewer than all studies, respectively. “Proportion” and “Signal” indicate the proportion of features for which signal was added and the magnitude of added signal, respectively.

A) Two studies. Full simulation results are shown in Supplemental Table S1.
B) Three studies. Full simulation results are shown in Supplemental Table S2.

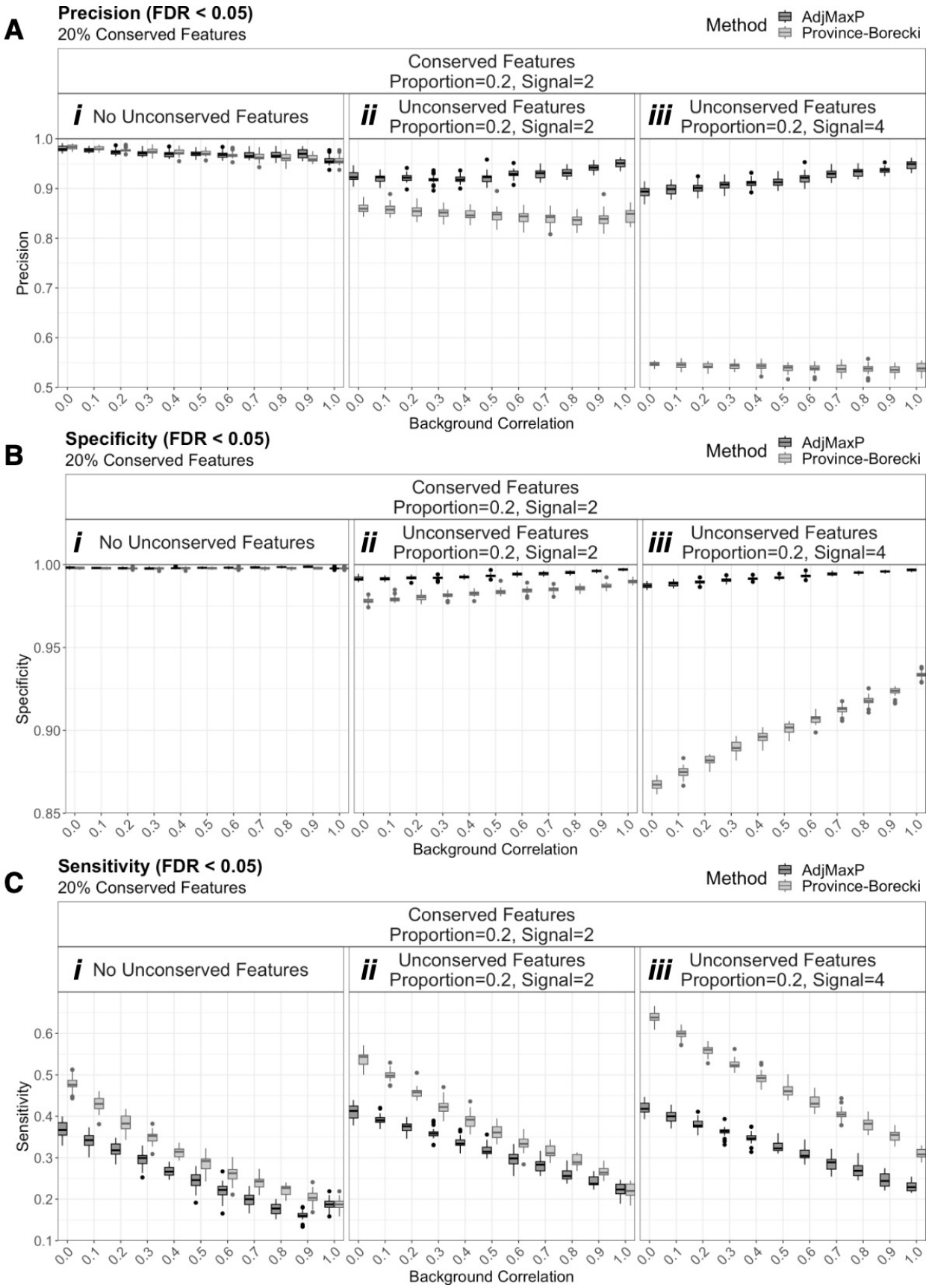
A
Precision (FDR < 0.05)
20% Conserved Features
Method
AdjMaxP
Province-Borecki
Conserved Features
Proportion=0.2, Signal=2
i No Unconserved Features
ii Unconserved Features
Proportion=0.2, Signal=2
iii Unconserved Features
Proportion=0.2, Signal=4
Precision
Background Correlation
B
Specificity (FDR < 0.05)
20% Conserved Features
Method
AdjMaxP
Province-Borecki
Conserved Features
Proportion=0.2, Signal=2
i No Unconserved Features
ii Unconserved Features
Proportion=0.2, Signal=2
iii Unconserved Features
Proportion=0.2, Signal=4
Specificity
Background Correlation
C
Sensitivity (FDR < 0.05)
20% Conserved Features
Method
AdjMaxP
Province-Borecki
Conserved Features
Proportion=0.2, Signal=2
i No Unconserved Features
ii Unconserved Features
Proportion=0.2, Signal=2
iii Unconserved Features
Proportion=0.2, Signal=4
Sensitivity
Background Correlation

Figure 2: Comparison of precision, specificity, and sensitivity from simulations of two studies with 20% conserved features, based on an FDR corrected q-value threshold of 0.05.

Boxplots reflect the distribution of performance at FDR q-value threshold, 0.05, for 25 simulations of 10,000 shared features at different levels of background correlation and unconserved signal, across simulations of two studies with 20% conserved features. "Conserved" and "Unconserved" features refer to features for which signal was added (i.e. deviate from the null distribution) across all studies or fewer than all studies, respectively. "Proportion" and "Signal" indicate the proportion of features for which signal was added and the magnitude of added signal, respectively. Full simulation results are shown in Supplemental Table S1.

A) Precision
B) Specificity
C) Sensitivity

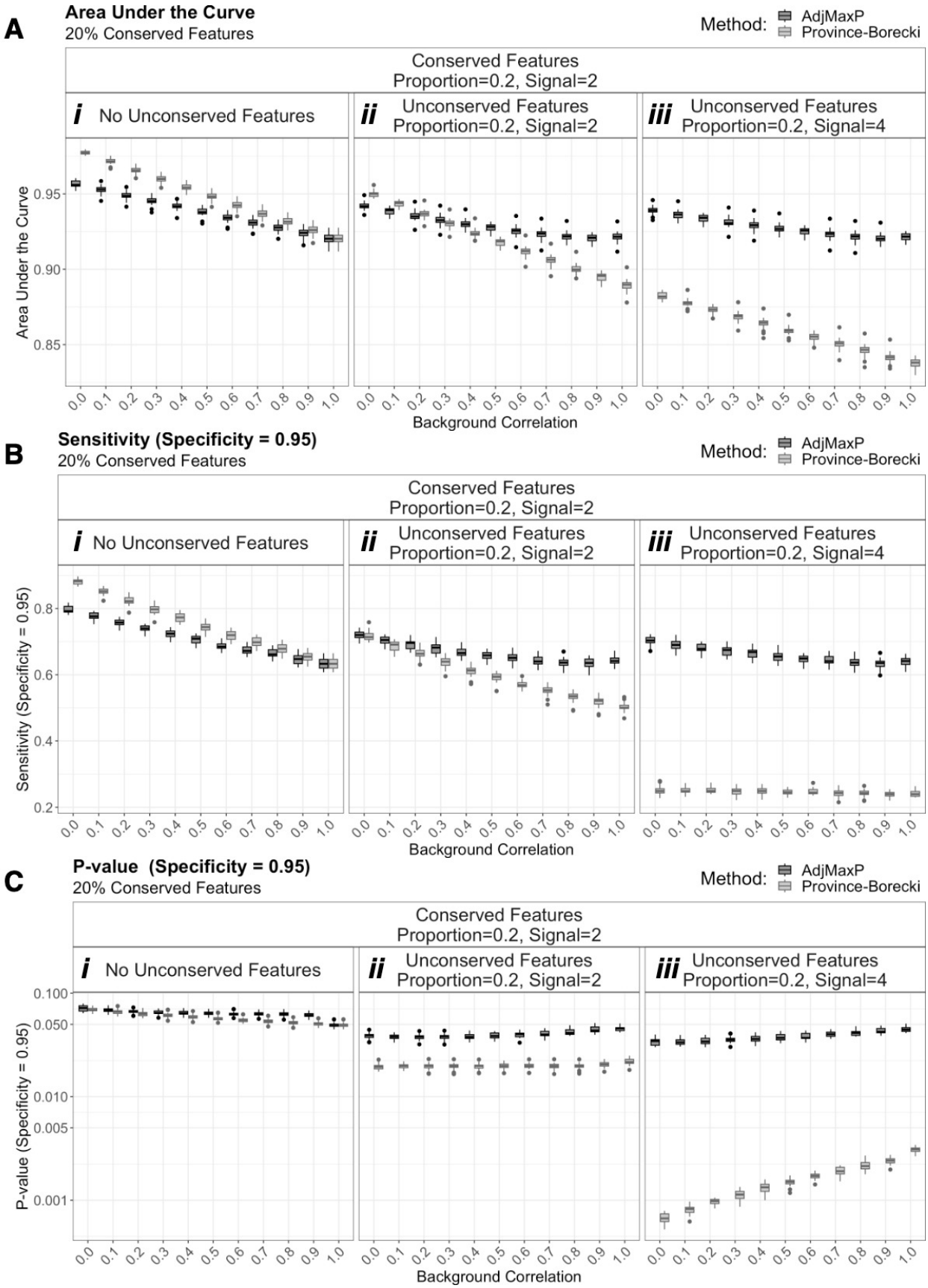
A
Area Under the Curve
20% Conserved Features
Method: AdjMaxP Province-Borecki
Conserved Features Proportion=0.2, Signal=2
i No Unconserved Features
ii Unconserved Features Proportion=0.2, Signal=2
iii Unconserved Features Proportion=0.2, Signal=4
Area Under the Curve
0.95
0.90
0.85
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
Background Correlation
B
Sensitivity (Specificity = 0.95)
20% Conserved Features
Method: AdjMaxP Province-Borecki
Conserved Features Proportion=0.2, Signal=2
i No Unconserved Features
ii Unconserved Features Proportion=0.2, Signal=2
iii Unconserved Features Proportion=0.2, Signal=4
Sensitivity (Specificity = 0.95)
0.8
0.6
0.4
0.2
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
Background Correlation
C
P-value (Specificity = 0.95)
20% Conserved Features
Method: AdjMaxP Province-Borecki
Conserved Features Proportion=0.2, Signal=2
i No Unconserved Features
ii Unconserved Features Proportion=0.2, Signal=2
iii Unconserved Features Proportion=0.2, Signal=4
P-value (Specificity = 0.95)
0.100
0.050
0.010
0.005
0.001
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
Background Correlation

Figure 3: Comparison of performance under threshold variable performance from simulations of two studies with 20% conserved features, based on an FDR corrected q-value threshold of 0.05.

Boxplots reflect the distribution of performance for 25 simulations of 10,000 shared features at different levels of background correlation and unconserved signal, across simulations of two studies with 20% conserved features. “Conserved” and “Unconserved” features refer to features for which signal was added (i.e. deviate from the null distribution) across all studies or fewer than all studies, respectively. “Proportion” and “Signal” indicate the proportion of features for which signal was added and the magnitude of added signal, respectively. Full simulation results are shown in Supplemental Table S1.

A) Area under the curve.
B) Sensitivity of conserved feature identification when specificity is equal 0.95.
C) Nominal p-value threshold when specificity is equal to 0.95.

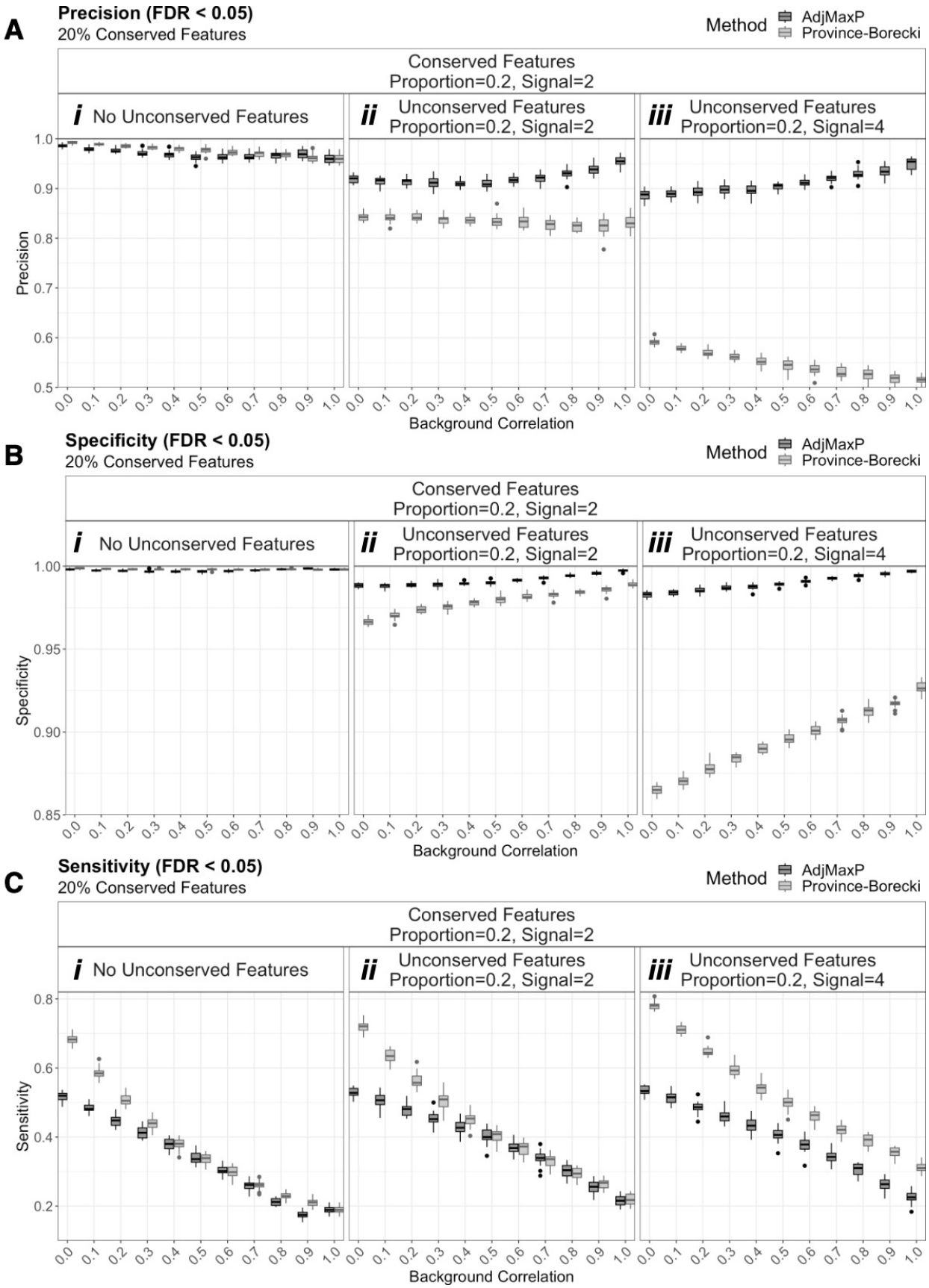
A
Precision (FDR < 0.05)
20% Conserved Features
Method
AdjMaxP
Province-Borecki
Conserved Features
Proportion=0.2, Signal=2
i No Unconserved Features
ii Unconserved Features
Proportion=0.2, Signal=2
iii Unconserved Features
Proportion=0.2, Signal=4
Precision
Background Correlation
B
Specificity (FDR < 0.05)
20% Conserved Features
Method
AdjMaxP
Province-Borecki
Conserved Features
Proportion=0.2, Signal=2
i No Unconserved Features
ii Unconserved Features
Proportion=0.2, Signal=2
iii Unconserved Features
Proportion=0.2, Signal=4
Specificity
Background Correlation
C
Sensitivity (FDR < 0.05)
20% Conserved Features
Method
AdjMaxP
Province-Borecki
Conserved Features
Proportion=0.2, Signal=2
i No Unconserved Features
ii Unconserved Features
Proportion=0.2, Signal=2
iii Unconserved Features
Proportion=0.2, Signal=4
Sensitivity
Background Correlation

Figure S1: Comparison of precision, specificity, and sensitivity from simulations of three studies with 20% conserved features, based on an FDR corrected q-value threshold of 0.05.

Boxplots reflect the distribution of performance at FDR q-value threshold, 0.05, for 25 simulations of 10,000 shared features at different levels of background correlation and unconserved signal, across simulations of three studies with 20% conserved features. "Conserved" and "Unconserved" features refer to features for which signal was added (i.e. deviate from the null distribution) across all studies or fewer than all studies, respectively. "Proportion" and "Signal" indicate the proportion of features for which signal was added and the magnitude of added signal, respectively. Full simulation results are shown in Supplemental Table S2.

A) Precision
B) Specificity
C) Sensitivity

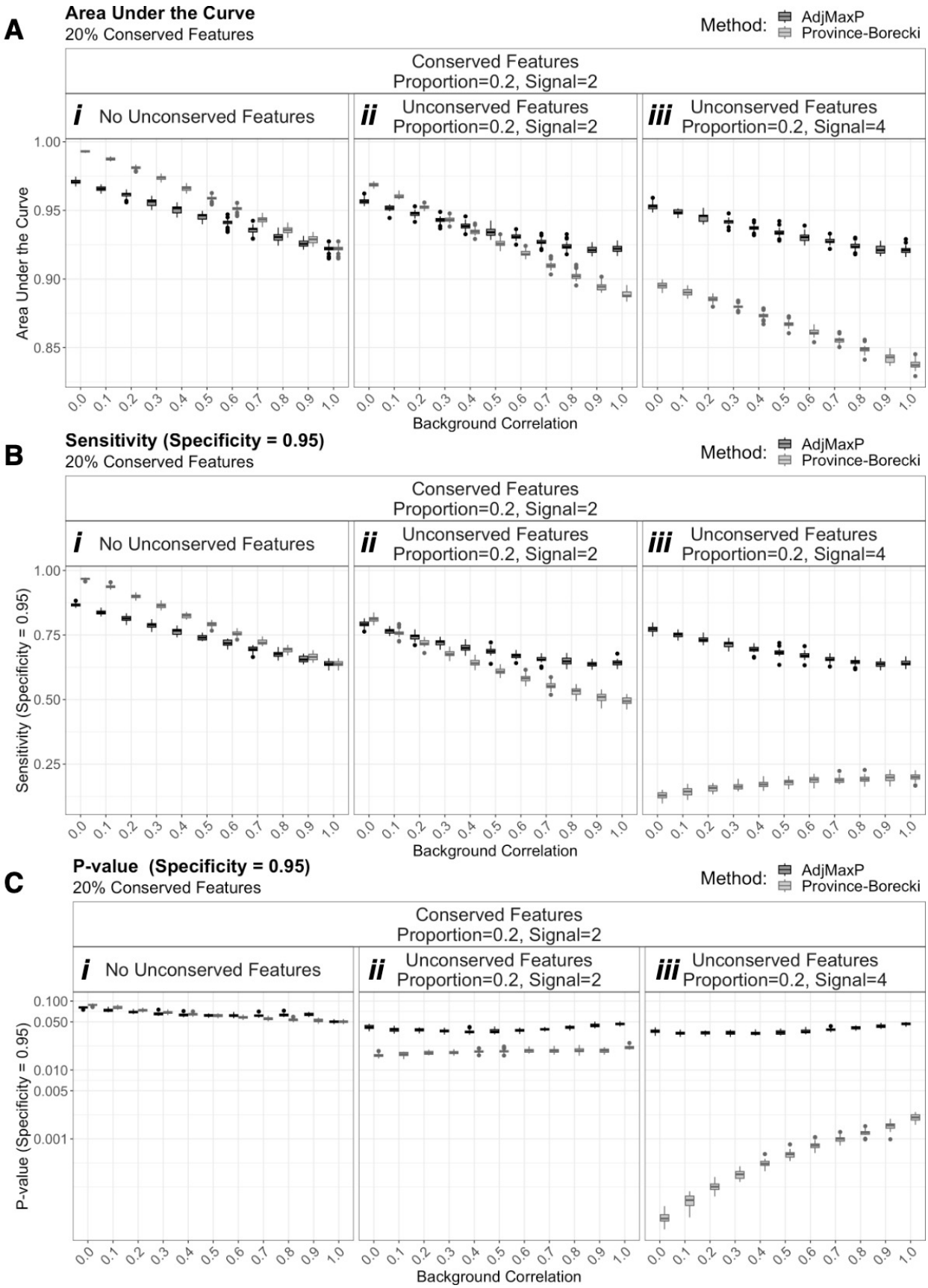
A
Area Under the Curve
20% Conserved Features
Method: AdjMaxP Province-Borecki
Conserved Features Proportion=0.2, Signal=2
i No Unconserved Features
ii Unconserved Features Proportion=0.2, Signal=2
iii Unconserved Features Proportion=0.2, Signal=4
Area Under the Curve
1.00
0.95
0.90
0.85
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
Background Correlation
B
Sensitivity (Specificity = 0.95)
20% Conserved Features
Method: AdjMaxP Province-Borecki
Conserved Features Proportion=0.2, Signal=2
i No Unconserved Features
ii Unconserved Features Proportion=0.2, Signal=2
iii Unconserved Features Proportion=0.2, Signal=4
Sensitivity (Specificity = 0.95)
1.00
0.75
0.50
0.25
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
Background Correlation
C
P-value (Specificity = 0.95)
20% Conserved Features
Method: AdjMaxP Province-Borecki
Conserved Features Proportion=0.2, Signal=2
i No Unconserved Features
ii Unconserved Features Proportion=0.2, Signal=2
iii Unconserved Features Proportion=0.2, Signal=4
P-value (Specificity = 0.95)
0.100
0.050
0.010
0.005
0.001
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
Background Correlation

Figure S2: Comparison of performance under threshold variable performance from simulations of three studies with 20% conserved features, based on an FDR corrected q-value threshold of 0.05.

Boxplots reflect the distribution of performance for 25 simulations of 10,000 shared features at different levels of background correlation and unconserved signal, across simulations of three studies with 20% conserved features. “Conserved” and “Unconserved” features refer to features for which signal was added (i.e. deviate from the null distribution) across all studies or fewer than all studies, respectively. “Proportion” and “Signal” indicate the proportion of features for which signal was added and the magnitude of added signal, respectively. Full simulation results are shown in Supplemental Table S1.

A) Area under the curve.
B) Sensitivity of conserved feature identification when specificity is equal 0.95.
C) Nominal p-value threshold when specificity is equal to 0.95.

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