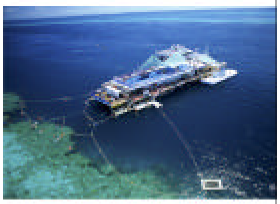

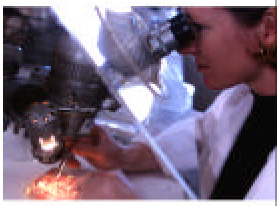

Analyses of crown-of-thorns starfish data from the fine-scale surveys and the long-term monitoring program manta tow surveys

Glenn De'ath

Australian Institute of Marine Science
and
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CRC REEF RESEARCH CENTRE TECHNICAL REPORT NO 47

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CONTENTS

EXECUTIVE SUMMARY

This report compares the use of fine-scale SCUBA (FSS) and manta tow (MT) for surveys of crown-of-thorns starfish (*Acanthaster planci* : COTS). In particular we compare: (1) how well FSS and MT predict outbreaks, (2) FSS and MT information based on reefs surveyed by both methods, and (3) patterns of current outbreaks based on both methods. Additionally, we assess the effectiveness of the sampling designs used in FSS.

FFS surveys record both count and size information on COTS varying from juveniles through to mature adults, whereas MT surveys are restricted to counts of mature adults. Both methods record additional information such as benthos cover. Despite the more limited information, MT better predict outbreaks than FSS. For comparable reefs, the accuracy of predictions are 88% and 76% respectively. This is probably due to two reasons

1. COTS are highly mobile and tend to aggregate. The larger area covered by MT surveys more than offsets the lower level of information per unit area, and the probability of completely missing COTS aggregations is also reduced.
2. The FSS counts of juveniles and immature adults are poor predictors of populations in following years. Juveniles in particular are severely undercounted, most likely due to the fact that they are almost totally cryptic during the day, and only emerge to feed at night. Nocturnal surveys could help solve this problem.

Data from MT surveys also better predict hard coral cover though this is a secondary issue.

MT and FSS surveys covered the same reefs in the same years for 34 surveys. Of these surveys, FSS gave higher estimates of mature adults by a factor of 2.76 (95% CI = 2.37, 4.48) compared to calibrated manta tow estimates. These differences in counts are possibly due to: (a) under-estimation by MT due to factors such as narrowed search path and / or reduced attention, (b) inaccuracy of the calibrations, and (c) FSS transects being located in areas favouring COTS.

FSS declared 12 of 34 (35%) of common reef-years to be outbreaking (> 1 COT per 250 sq m transect) compared to MT declaring only 3 of 34 (9%) as active outbreaks (AOs > 1 COT per tow), and an additional 3 (9%) as incipient outbreaks (IOs > 0.22 COTS per tow). Declaring MT outbreaks as > 0.1 COTS per tow gives 12 outbreaks (same as FSS) with 9 of the 12 in common, and 28 / 34 (82%) AO and non-AO agreements between the two methods. The levels at which MT surveys declare outbreaks is too low.

The following options should be considered:

1. Reefs with levels of cots > 0.22 per tow should be classified as active outbreaks (AO)
2. Reefs with levels of cots > 0.1 per tow should be classified as potential outbreaks (PO)

The new MT ratings would be less severe than FSS current criteria, but would lead to approximately 50% more AOs and 40% more outbreaks (AO + PO) being declared.

Both FSS and MT data show the southern drift of the current COTS outbreak (1991-2000) and the estimated rate of drift is 0.24° to 4° per year from both methods.

The sampling design of FSS surveys could be made more efficient by reducing the numbers of sites and possibly transects depending on a cost-benefit analysis.

OBJECTIVES

The objectives of this Report are as follows:

1. ***To determine how well FSS and MT predict outbreaks.***

   This includes discussion of the definition of outbreaks and determination of the best predictive methods, and best predictors of both COTS abundances and outbreaks, and hard coral cover. These are important issue for management; in particular the ability to predict transitions of reefs to high numbers of mature COTS that can result in severe depletion of hard coral cover. Given the structure of the data and the management requirements, prediction for one-year ahead on a single reef is the main focus.

2. ***Comparison of FSS and MT information on common reefs.***

   The effectiveness of this comparison is limited due to the moderate coincidence of reefs and sampling times of the two methods, but nonetheless shows important similarities and differences in the relative performance of the two methods.

3. ***To assess the patterns of current outbreaks.***

   We examine how FSS and MT reveal patterns of outbreaks. MT has a greater spatial and temporal spread, but both types of survey cover the current COTS outbreaks on mid-shelf reefs in the central Great Barrier Reef.

4. ***Assessment of FSS as to the intensity of sampling.***

   FSS typically uses 20 sites per reef (each with 2 transects). The precision of this sampling scheme is assessed using components of variance, and the precision of alternative sampling schemes is examined.

INTRODUCTION

The crown-of-thorns starfish *(Acanthaster planci*; COTS; Moran 1986) has been the subject of intense scientific activity since the mid 1980s. A major part of that activity has involved extensive surveys of the Great Barrier Reef (GBR) with the aim of detecting and monitoring COTS outbreaks. Accurate assessment of crown-of-thorns starfish *(Acanthaster planci;* COTS) populations and their potential to outbreak can clearly be useful for reef management. However, it is difficult to assess COTS populations due to: (1) rapid changes in population size, (2) aggregation of individuals to form large groups, (3) cryptic behaviour which is both diurnal and age dependent, and (4) high levels of mobility across depths and around the reef perimeters.

The primary survey method for COTS has been the manta tow (Kenchington 1984, Moran et al 1989; Moran and De'ath 1992 a,b). Observers are towed around the reef perimeter and they record counts of starfish and additional information. Each tow lasts ~2 minutes and covers ~200m, with on average 50-60 tows per reef. The manta tow method covers large areas compared to the more traditional SCUBA transect surveys, and is particularly effective for COTS due to their high mobility and aggregative behaviours (Moran and De'ath 1992 a,b; De'ath 1998 a,b). Although manta tow surveys are consistent between observers (Moran and De'ath 1992 b), compared to SCUBA transect surveys, they do substantially undercount COTS by 60%-90% dependent on COTS density. However, these counts can be calibrated to provide relatively accurate density estimates (De'ath 1992).

An alternative to MT is fine-scale surveys (FSS; Engelhardt *et al* 2000). FSS use SCUBA searches of typically 20 sites per reef (each with 2 transects of ~ 250 sq m). FFS surveys are more intensive than MT and record both count and size information on COTS. They record information on juveniles through to mature adults, whereas MT surveys are restricted to counts of mature adults.

FSS and MT have different advantages for monitoring COTS. For example, if densities of starfish are low and there is a high level of aggregation, it is easy to miss the starfish using FSS. This could be countered by using large numbers of belt transects, but then FSS becomes prohibitively expensive. Conversely, MT undercounts COTS by 60 - 90% (Moran and De'ath 1992a), with the relative undercounting increasing with decreasing densities. MT counts can be calibrated for undercounting, but this introduces other inaccuracies. Also cryptic starfish and juveniles will almost certainly be missed using MT.

COTS outbreaks have been defined in many ways (Moran and De'ath 1992a, Engelhardt *et al* 2000). Given an objective of this study is to assess the predictability of outbreaks for both FSS and MT, it is desirable to have outbreak criteria that are: (1) comparable for both methods, (2) ecologically sensible, and (3) preferably simple. Research based on MT suggested two levels of COTS densities for defining outbreaks: 0.22 and 1.0 COTS per tow (manta tow COTS are predominantly adults), equivalent to ~ 1500 and ~ 4000 per sq km when calibrated (Moran and De'ath 1992a). The lower level has been suggested as a maximum "sustainable" level of COTS, and the higher as a level at which severe damage occurs. FSS define several types of outbreaks (Engelhardt *et al* 2000), including "spot" and "incipient" outbreaks, dependent on the spatial distribution and the age of the COTS. For an active outbreak (AO) of mature adults, the level is > 0.75 COTS per 250 sq m transect on both the front and back of a reef. Assuming FSS find all COTS, this is equivalent to 3000 per sq km if both front and back have equal densities of COTS. In practice this probably averages out at ~ 4000 - 5000 per sq km since there are ~ twice as many mature adult COTS on the backs of reefs. Thus FSS AOs are equivalent to MT tow AOs defined as > 1.0 COTS per tow. To facilitate comparisons on a reef basis, we later use the definition of FSS AOs as > 1.0 mature adult COTS per 250 sq m transect.

The Australian Institute of Marine Science Long Term Monitoring Program (LTMP) uses MT to classify reef status (active outbreak = AO, incipient outbreak = IO, recovery = RE, non-outbreak = NO) in a complex manner dependent on live and dead coral cover and the history of the reefs status (see Appendix Two). In this report we examine the levels of COTS and coral cover for defining outbreaks. The fact that reef status at a given time is based on both current and previous survey information precludes these estimates of reef status to be used predictively, though we do present an analysis of these data.

There are major differences in the sample locations and times between FSS and MT. FSS cover mid-shelf reefs of the central GBR – an area that has had consistently high levels of COTS over the last 15 years. Conversely, MT cover much more of the GBR, both along and across the Reef. FSS surveys were conducted over 1994-2000, compared to MT surveys that were conducted over 1984-2000.

This Report focuses on predicting reef status and characteristics (COTS abundances, live and dead coral cover), and on comparing FSS and MT surveys for common "reef - years". We also present basic descriptive information. Reefs were used as the unit of study for which we assessed the predictive ability of these data, since (1) reefs are the management unit, and (2) the high-dynamics of COTS within reefs precludes prediction at smaller spatial scales. Although broader scales are of interest, the data are inadequate to quantify predictive ability at such scales, however we do present descriptive information at this level.

SUMMARY OF RESULTS

Fine-scale surveys

At the scale of regions, as opposed to individual reefs, the waves of cohorts from juveniles (< 1 yr) to immature adults (1 - 2 yrs) to mature adults (> 2 yrs) were detected across some years, but not consistently. FSS show the southern movement of the current wave in the central GBR. The sampling effort moves south with the wave. The estimated rate of movement is in the range (0.25 - 4^{o} per year).

At the individual reef level, the juvenile counts appear to be unreliable and are unable to predict immature populations. Also, the numbers of juveniles are far too low to account for immature and mature populations in subsequent years. Similarly the immature counts are unreliable predictors of matures. The low counts of juveniles and immatures are most likely due to the fact that small starfish are almost totally cryptic during the day and only venture out to feed at night (De'ath and Moran 1998a). If reliable estimates of juveniles are required then nocturnal surveys are probably necessary. Even then the relative composition of juveniles, immature and mature adults would need to be calibrated for their varying diurnal availability. A combination of previous mature COTS and previous cover of hard coral better predict mature COTS, but this predictive capacity is not great (21% of mature COTS variation).

When outbreaks were for FSS AOs as > 1.0 mature adult COTS per 250 sq m transect (~ 4000 per sq km), prediction of outbreaks had an estimated misclassification rate of 24%. Thus, compared to guessing (50% error) this improves our odds by a factor of 4 to 1.

Manta tow surveys

MT provided moderately reliable predictions of COTS per tow, accounting for 44% of predicted variance. It also gave fairly good predictions of live and dead coral cover. For all data MT prediction of outbreaks had a misclassification rate of 12%. When restricted to data comparable to the FSS surveys the misclassification was 18%; substantially lower than FFS predictions.

As with FSS, MT data show the southern movement of the current wave in the central GBR, and the sampling effort also moves south with the wave. The estimated rate of movement is in the range (0.25 - 4^{o} per year); similar for both survey methods. Additionally MT data show persistent outbreaks in the Swains and parts of the northern half of the GBR.

The manta tow survey reefs severely under-represent the inner third of the GBR, and given the recent increased focus on the inner reefs, this should be addressed.

Comparison of the fine-scale and manta tow surveys on common reefs

MT and FSS surveys cover the same spatial-temporal block for ~ 60 surveys of each with 34 reefs being surveyed in the same year by both methods. On the 34 common reef-years, FSS give higher estimates of mature adults by a factor of 2.76 (95% CI = 2.37, 4.48) compared to calibrated manta tow estimates (Moran and De'ath 1992b). These differences in counts are possibly due to: (a) under-estimation by MT due to factors such as narrowed search path and / or reduced attention, (b) inaccuracy of the calibrations, and (c) FSS transects being located in areas favouring COTS.

FSS declared 12 of 34 (35%) of common reef-years to be outbreaking (> 1 COT per 250 sq m transect) compared to MT declaring 3 of 34 (9%) as AOs (> 1 COT per tow), and an additional 3 (9%) as IOs (> 0.22 COTS per tow). Declaring MT outbreaks as > 0.1 COTS per tow give 12 outbreaks (same as FSS) with 9 of the 12 in common, and thus 28 / 34 (82%) AO and non-AO agreements between the two methods.

For MT outbreaking reefs (all data with >7 surveys) both AO and IO showed substantial declines in hard coral cover. Also, although IO refers to incipient outbreaks, only 3 of 36 IOs became AO; the rest became NO or RE or remained as IO. Incipient is clearly an inappropriate description.

These factors suggest we need to adjust MT outbreak criteria. AO and IO are levels which are experiencing high COTS numbers; if calibrations are correct then > 1500 per sq km (0.22 COTS per tow) and > 4000 (1.0 COTS per tow). If the FSS - MT correction is applied then 1.0, 0.22, and 0.1 COTS per tow 11000, 4900 and 3500 COTS per sq km.

The following options should be considered:

- Reefs with levels of cots > 0.22 per tow should be classified as active outbreaks (AO) [perhaps > 1 cot per tow = severe outbreak (SO)]
- Reefs with levels of cots > 0.1 per tow should be classified as potential outbreaks (PO) [or perhaps marginal outbreaks (MO)].

The new MT ratings would be less severe than FSS current criteria, but would lead to approximately 50% more AOs and 40% more outbreaks (AO + PO) being declared in total.

Assessment of FSS sampling design.

Analysis of the FSS data across a balanced subset of the data showed changes between reefs, zones and years and interactions of these factors. Strong zone effects and interactions with reef and years were particularly prominent, and, at least in part, reflect the high mobility of the COTS. It is possible that this mobility coupled with the relatively small area sampled when using the belts transects of FSS, results in the generally better performance of MT which sample a large fraction of reef area (typically 20 times as much).

The FSS sampling intensity is more than adequate to detect changes (using ANOVA / MANOVA and traditional hypotheses tests) in COTS abundances for all size-classes between reefs, zones and years and combinations thereof. The sampling intensity could be substantially reduced, certainly by a factor of 50%, if this was the only objective of the surveys.

ANALYTICAL METHODS

Prediction

Most ecological analyses are either descriptive or based on hypothesis tests and confidence intervals (classical inference). It is rare that the predictive capacity of ecological models is assessed. Accuracy of predictions can be estimated from the assumptions inherent in the model, e.g. the linear model with normal and independent errors. However, this often results in over-optimistic estimates of accuracy (Draper 1995), and alternative methods based directly on the data rather than model assumptions are preferable. Cross-validation (Ripley 1996) is the most widely preferred data-based method of obtaining good estimates of the accuracy of models. All estimates of predictive accuracy in this Report were based on cross-validation. For complex data involving non-linearities, the accuracy of models can often be improved by repeatedly fitting a particular type of model, e.g. a regression tree, from subsamples of the data, and then averaging the results (such as the predictions or parameter estimates) over the subsamples. Bagging (Breiman 1996) is an example of such a technique, and we use it in this Report. This can be improved by using adaptive methods whereby, in the series of averaged fits, subsequent fits are weighted such that data that are poorly predicted are given greater weight.

We will be modelling both numeric and categorical responses. For numeric responses we express accuracy the predicted mean square error, and report it as a fraction of the data variance; this is termed the relative error. For a perfectly accurate model this takes the value of zero, and increases with decreasing accuracy. For a model that is no better than using the overall mean of the sample data to predict all future observations, the relative error equals one. For categorical responses we estimate accuracy as the proportion of misclassifications relative to either "blind guessing", or more typically, relative to always predicting the most frequent class of the data ("informed guessing"). As an example consider data with 100 cases of which 60 are class A, 30 are B and 10 are C. If the estimated misclassification rate is 10 out of 100, then this has a relative error of 0.25 (10 errors compared to 40) compared to informed guessing or 0.20 (10/50) compared to blind guessing, These can also be usefully expressed as odds-ratios.

When predictions of categorical responses are involved, and actions are contingent on the predictions, it is important to consider the outcomes of those actions and to weight them accordingly. For example, medical diagnoses should favour making the error of a "diseased" diagnosis (and unnecessary treatment), as opposed to the error of a "non-diseased" diagnosis (and unnecessary death!). Similarly the error of misclassifying a non-outbreaking reef as an outbreak reef could be considered less costly than the converse error. Different losses can be built into models such as trees to account for such inequalities of outcome. Since such losses are unspecified for the risk of COTS outbreaks, such analyses are not included. However, it should be realised that such approaches are available if risk analyses are to be considered in the future.

The predictive models in this Report were based on linear models as well as classification and regression trees. The latter are briefly outlined below, and are described in detail in De'ath and Fabricius (2000) and Breiman (1984)

Trees

Classification and regression trees are ideally suited for the analysis of complex ecological data. For such data, we require flexible and robust analytical methods, which can deal with non-linear relationships, high-order interactions, and missing values. Despite such difficulties, the methods should be simple to understand and give easily interpretable results. Trees explain variation of a single response variable by repeatedly splitting the data into more homogeneous groups, using combinations of explanatory variables that may be categorical and / or numeric. Each group is characterised by a typical value of the response variable, the number of observations in the group, and the values of the explanatory variables that define it. The tree is represented graphically and this aids exploration and understanding.

Trees can be used for interactive exploration, and description and prediction of patterns and processes. Advantages of trees include: (1) the flexibility to handle a broad range of response types, including numeric, categorical, ratings and survival data, (2) invariance to monotonic transformations of the explanatory variables, (3) ease and robustness of construction, (4) ease of interpretation, and (5) the ability to handle missing values in both response and explanatory variables. Thus, trees complement, or represent an alternative, to many traditional statistical techniques, including multiple regression, analysis of variance, logistic regression, log-linear models, linear discriminant analysis and survival models.

THE FINE-SCALE SURVEYS: AN OVERVIEW OF THE DATA

Preliminary data investigations

In this section we present some summaries and syntheses of the FSS data. The survey reefs are mid-shelf reefs in the central third of the GBR covering 14.8°S to 18.8 °S. The data were provided in two forms. First, size-class frequency data for each transect -- the size classes were labelled as juveniles, immature and mature adults, with an argument that these size classes approximated 1-year age cohorts. Hereafter these are referred to as juveniles, immatures and matures. Second, individual sizes of observed COTS together with depth and transect information. Both of these data sets were used in the following analyses. There were minor anomalies in the data.

The data from all transects (n = 5400) (see Engelhardt *et al* 2000 for details) are unbalanced with respect to years, reefs and reef zone (front, back, flank etc). The data covered 6 consecutive years (1994-1995 to 1999-2000) and 38 reefs; a total of 131 reef-year combinations. The locations of the reefs are shown in Figure 1, and the sampling years for reach reef, together with a measure of the mean abundance of total COTS are shown in Figure 2. The southern progression of the sampling scheme over time can also be seen (Fig. 2). Over all surveys, a total of 17851 COTS were recorded. COTS were observed on 61.7% of transects (mean = 3.31, range = 0 - 106); mature adults on 39.5% (1.63, 0 - 79), immature adults on 32.0% (0.92, 0 - 51) and juveniles on 20.8% (0.76, 0 - 36). For whole reefs total COTS ranged from (2 - 1050), mature adults (0 - 801), immature adults (0 - 406) and juveniles (0 - 365). The abundances (> 0.5 COTS per transect) of mature, immature and juvenile starfish over the 6 years are shown in Figure 3.

Large numbers of immature and matures are seen in 95-96 (Fig. 3), but juveniles and immature are not evident in the preceding year. There are also several instances immature adults not being preceded by juveniles. Detailed plots of the size frequency data for individual reefs over time, together with hard coral cover are shown in Appendix Two.

The shifts in the size-frequency data over time (Figs. 4 and 5) show reasonably coherent patterns other than for the lack of COTS in the first year of surveys, and the age-cohorts show similar trends but with less resolution (Fig. 6).

The locations at which COTS were found varied strongly with age-class, with matures favouring backs of reefs and juveniles favouring fronts of reefs (Fig. 7).

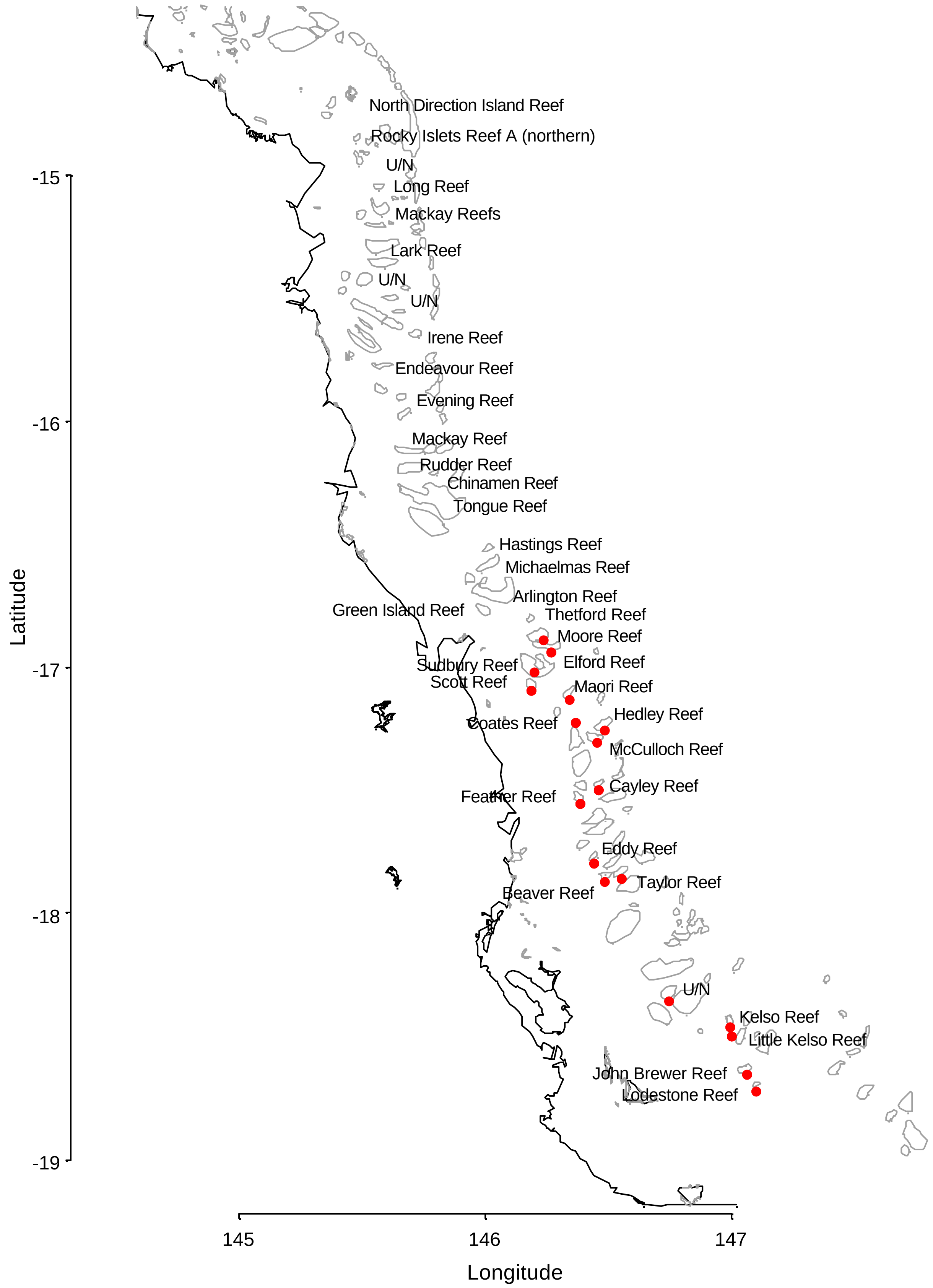


Figure 1. Locations of the 38 reefs used in the fine-scale surveys.

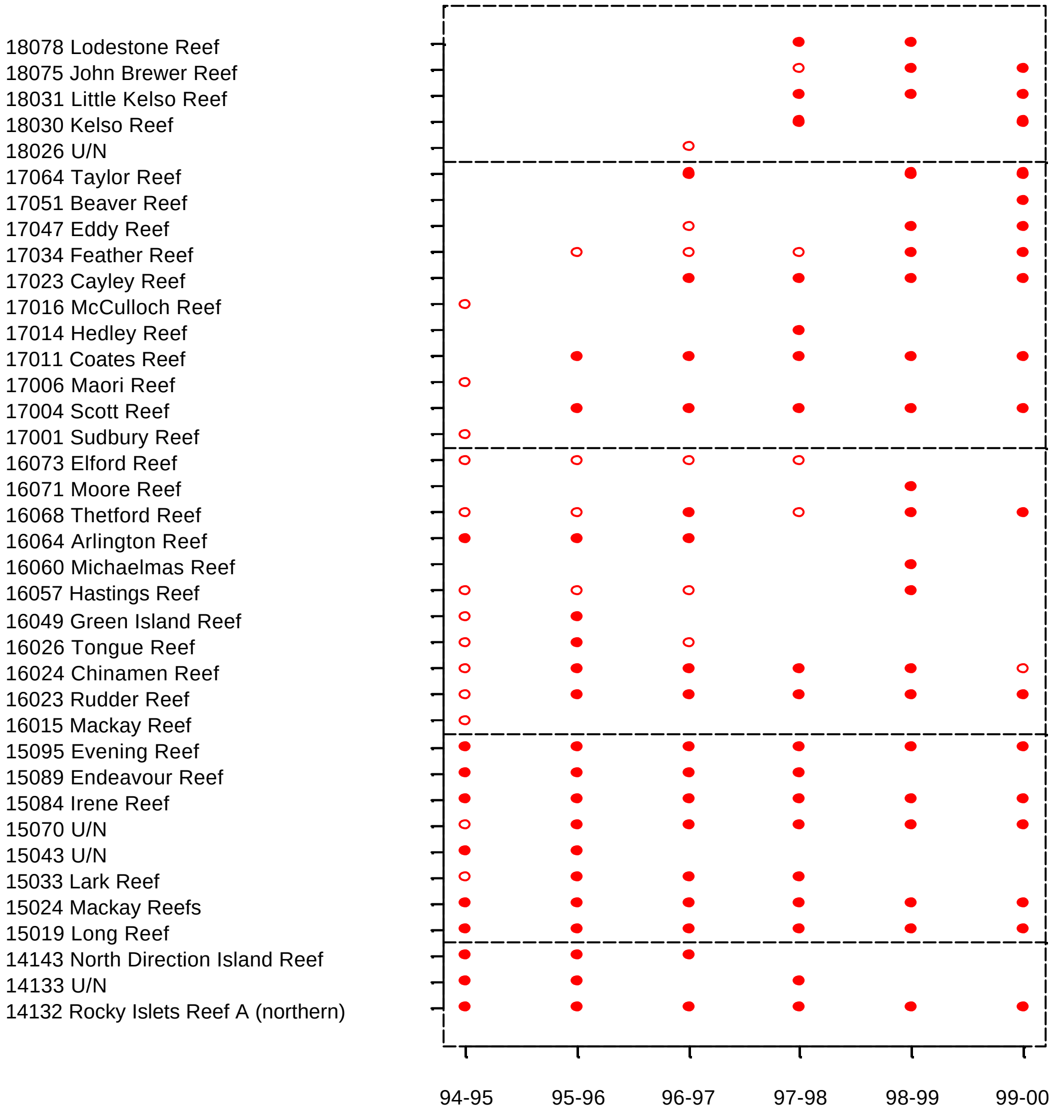


Figure 2. Sampling years of the 38 reefs used in the fine-scale surveys. The dots denote that a reef was sampled in a given year and the dots are filled when the mean number of COTS per transect were >1.

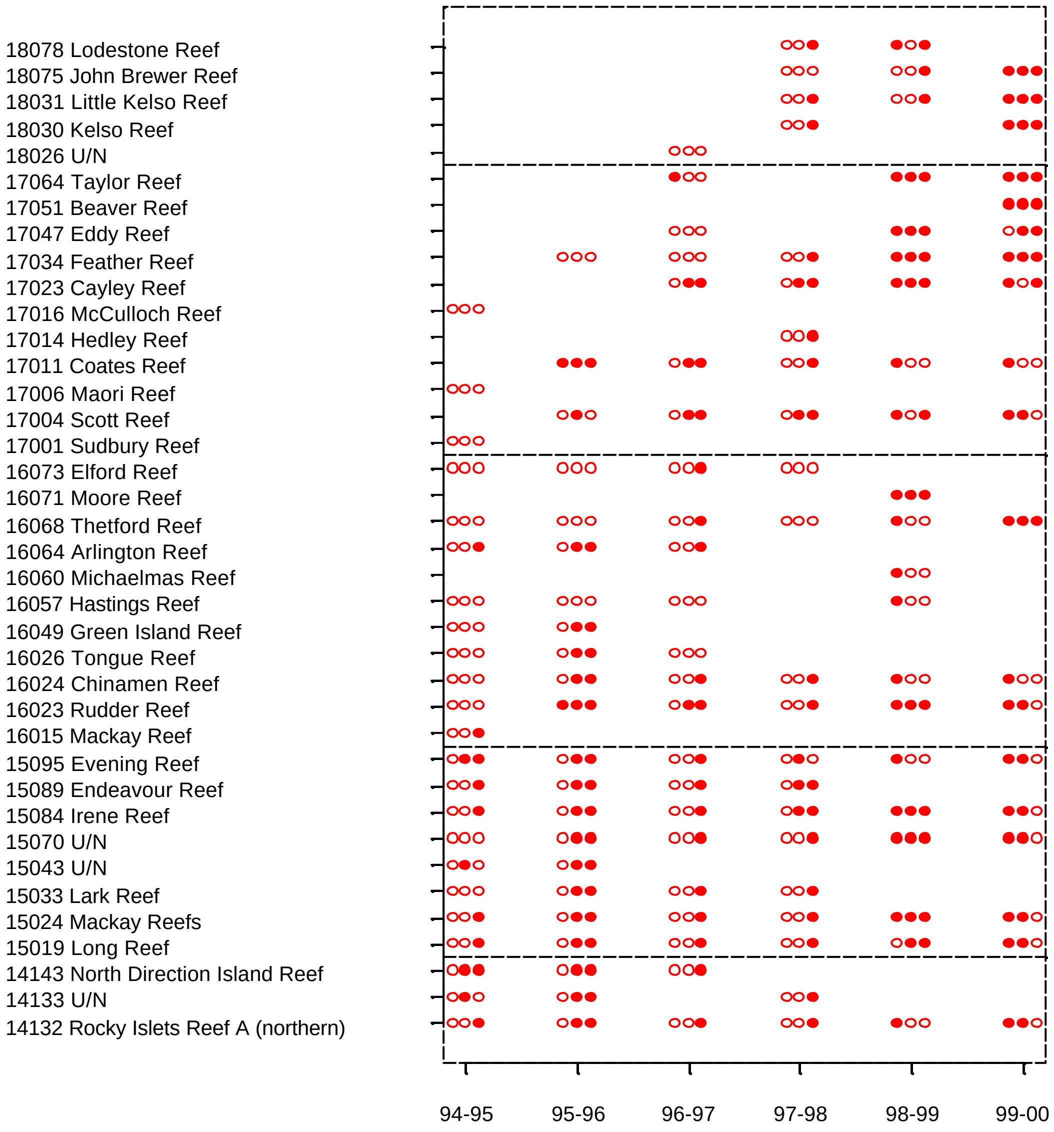


Figure 3. Sampling years of the 38 reefs used in the fine-scale surveys, showing the levels of abundances of COTS for juveniles (left of the three circles), immature (center of the three circles), and matures (right of the three circles). The dots are filled when the mean number of COTS per transect were >0.5.

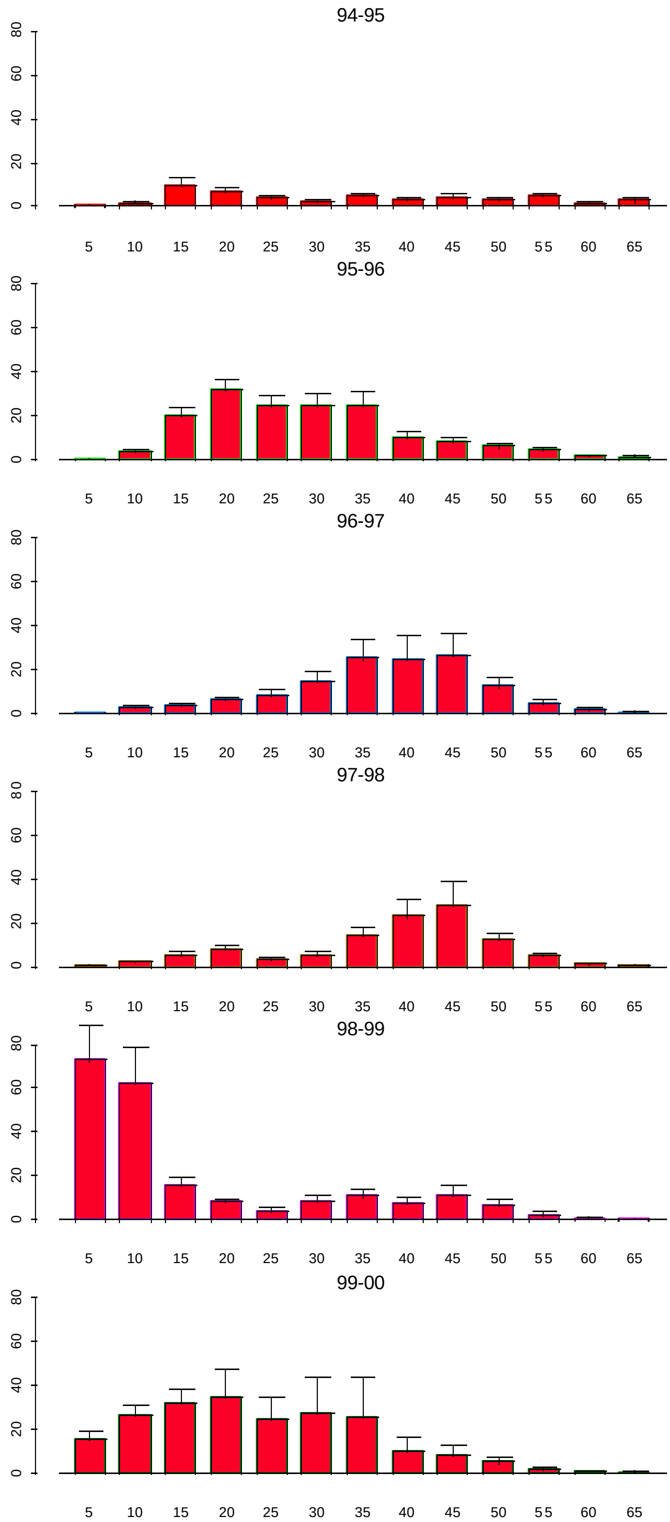


Figure 4. Size-frequency distributions of COTS for the 6 sampling years. The size groups are: s5 = (0, 5), s10 = (5+, 10), etc.

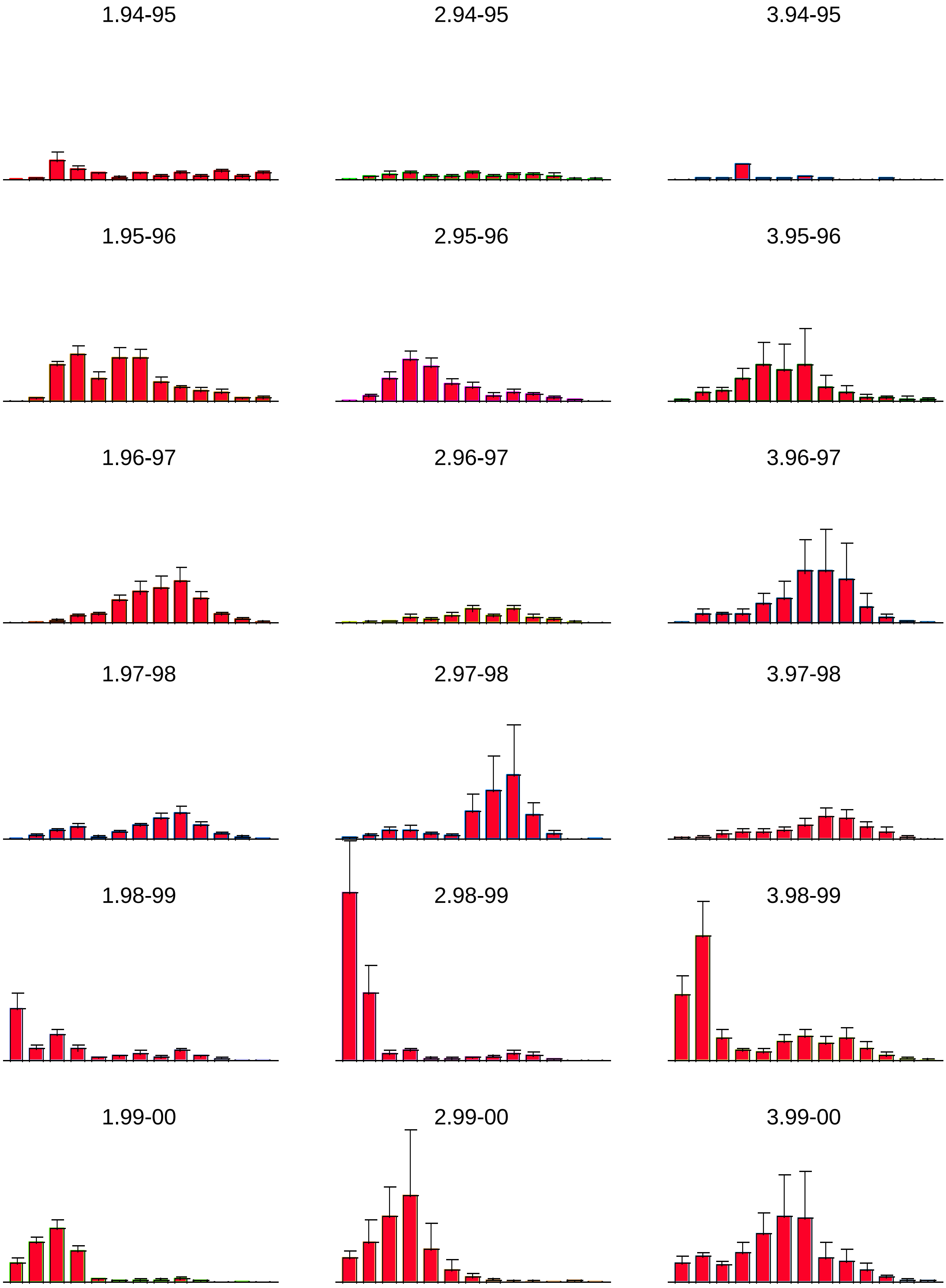


Figure 5. Relative size-frequency distributions of COTS for the 6 sampling years, broken down by three latitudinal bands (1 = northern third of FSS reefs, 2 = central third, and 3 = southern third).

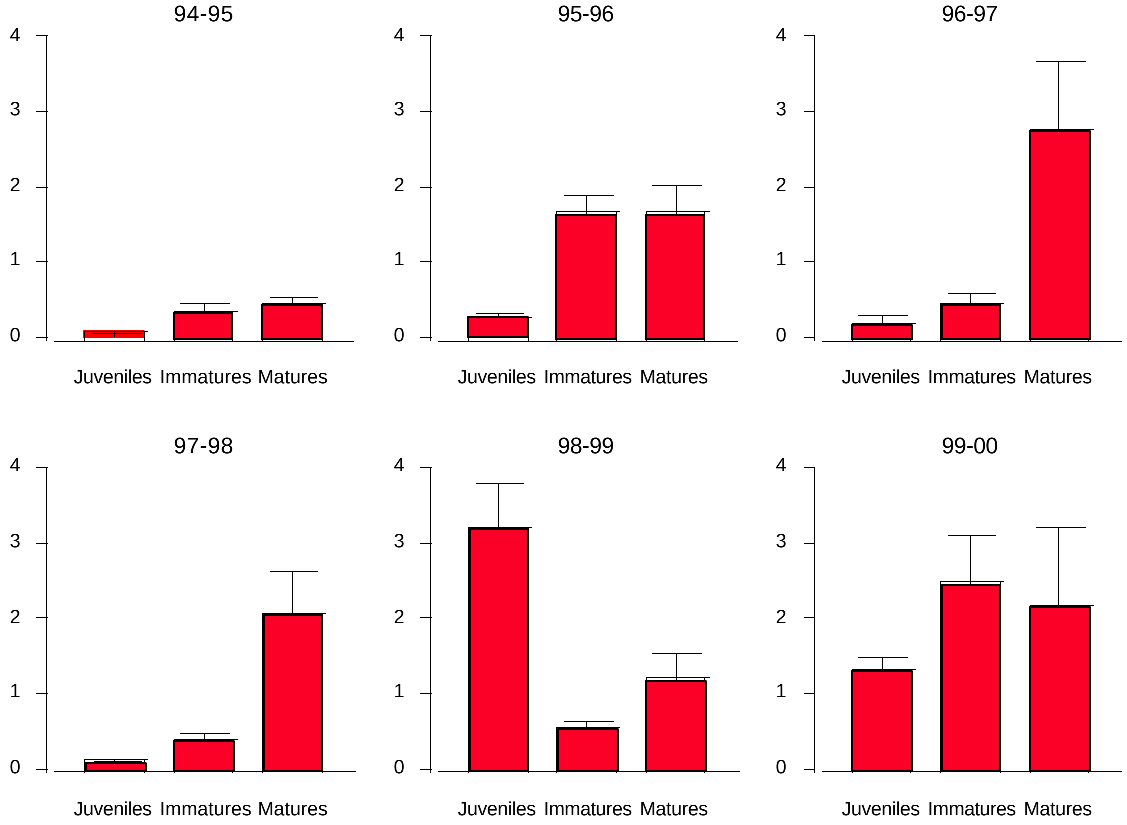


Figure 6. Plots showing the abundances (per transect) of juveniles, and immature and mature adults for the 6 years of surveys.

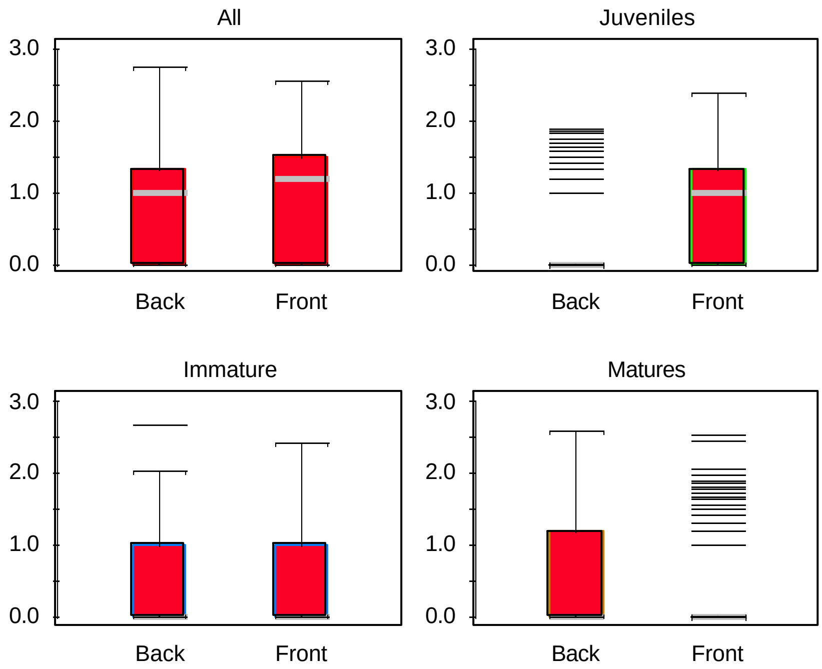


Figure 7. Boxplots showing the distribution of COTS on the backs and fronts of reefs. Juveniles show a strong preference for the fronts of reefs, whereas mature adults prefer backs of reefs. For all boxplots, the box indicates the 25 and 75%iles, the central bar is the 50%tile (median), the tails include 'typical values' and the horizontal thin lines are outliers.

THE MANTA TOW SURVEYS: AN OVERVIEW OF THE DATA

Preliminary data investigations

Data on 447 reefs collected over the period 1984-2000, and comprising 1751 surveys, were used for these analyses. The number of surveys per reef varied from 1 to 15. The data comprised MT counts of COTS, cover estimates for live and dead hard coral cover, and the status of each reef defined as either active outbreak (AO), incipient outbreak (IO), recovery (RE) or non-outbreak (NO). The mean number of COTS per tow varied from 0 to 55.5, with 67.9% of reefs having no recorded COTS. Live and dead hard coral cover averaged 25.7% (range 1.5 - 81.5) and 5.7% (0 - 71.3) respectively.

The distribution of surveys from the manta tows, the three major outbreaks (AO and IO) and the non-outbreaking (NO) and recovery (RE) reefs are shown in Figures 8(a-c). It is worth noting that some areas of the GBR have been unaffected by COTS for the whole period 1984-2000.

MT reefs are under-represented on the inner quarter of the GBR by a ratio of 1:3 (Fig. 9), and given the current focus on inshore effects this imbalance should be addressed.

For predictive analyses, data including only reefs with > 7 visits were used, since this gives most reefs which have previous visits within 2 years, and enables us to study change between years. Live coral cover varied little over the period 1986-2000 (Fig. 10), whereas dead coral cover shows a sharp decline (Fig. 10). Total coral cover shows a decline over that period, and suggests dead coral may not be consistently replaced after COTS outbreaks and other impacts.

The complexity of the definitions of reef status (Appendix One) leads to anomalies whereby there are no differences between numbers of COTS per tow and levels of dead coral cover for dead and non-outbreaking reefs (Figs 11 and 12), and relatively small differences in live coral cover.

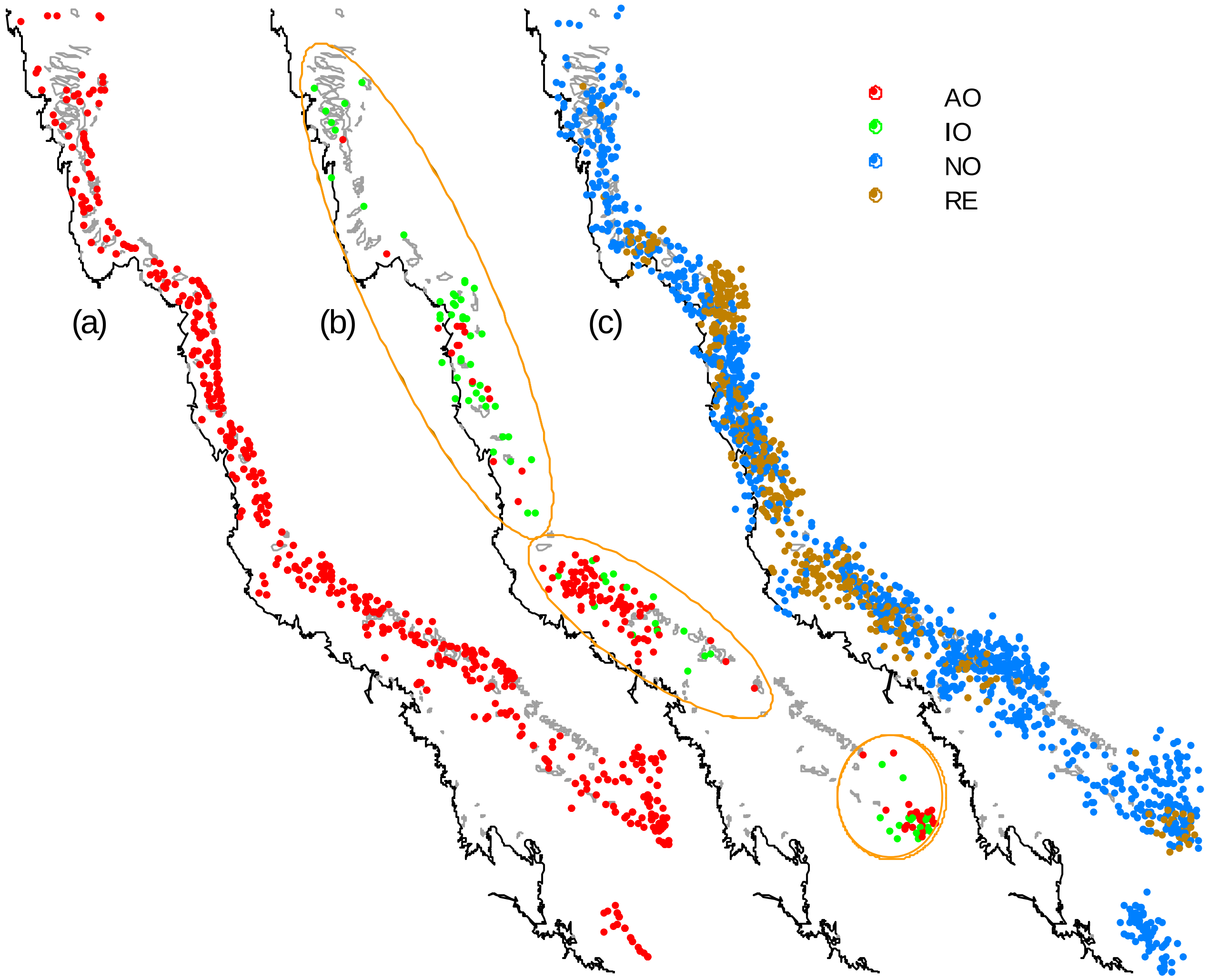


Figure 8. Sampling locations (a) of all manta tow reefs from 1986-2000, of AO and IO reefs (b) with the major outbreaks in orange ellipses, and NO and RE reefs (c). Points in (b) and (c) are jittered to reveal overlaid points.

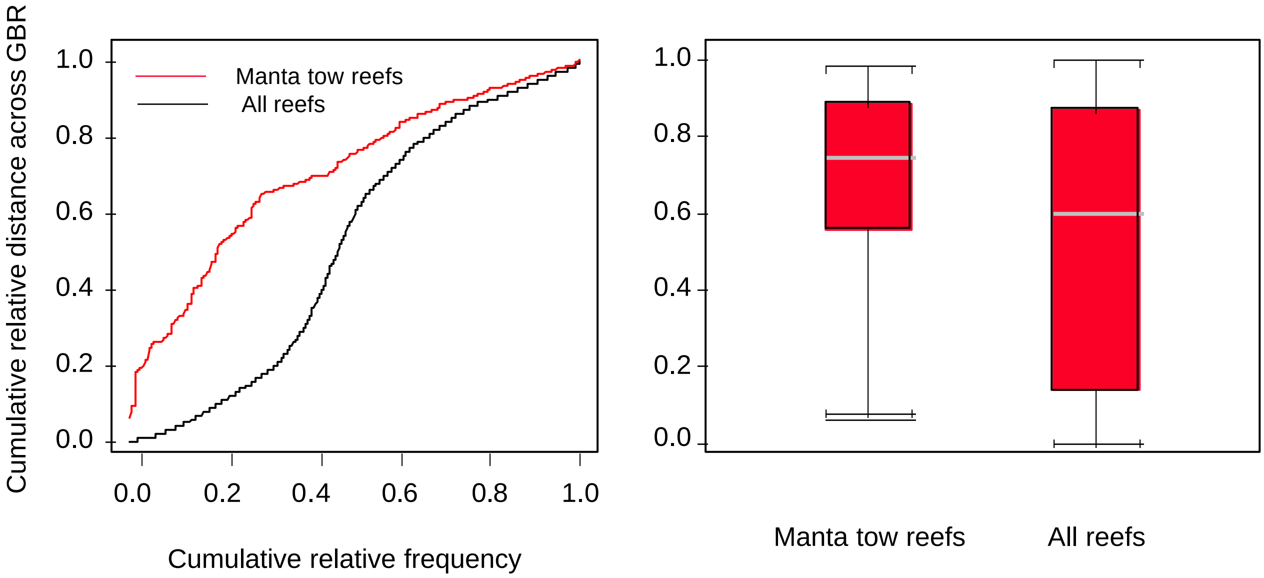


Figure 9. Sampling locations of manta tow reefs relative to all GBR reefs. Manta tow reefs are under-represented on the inner quarter of the GBR by a ratio of 1:3.

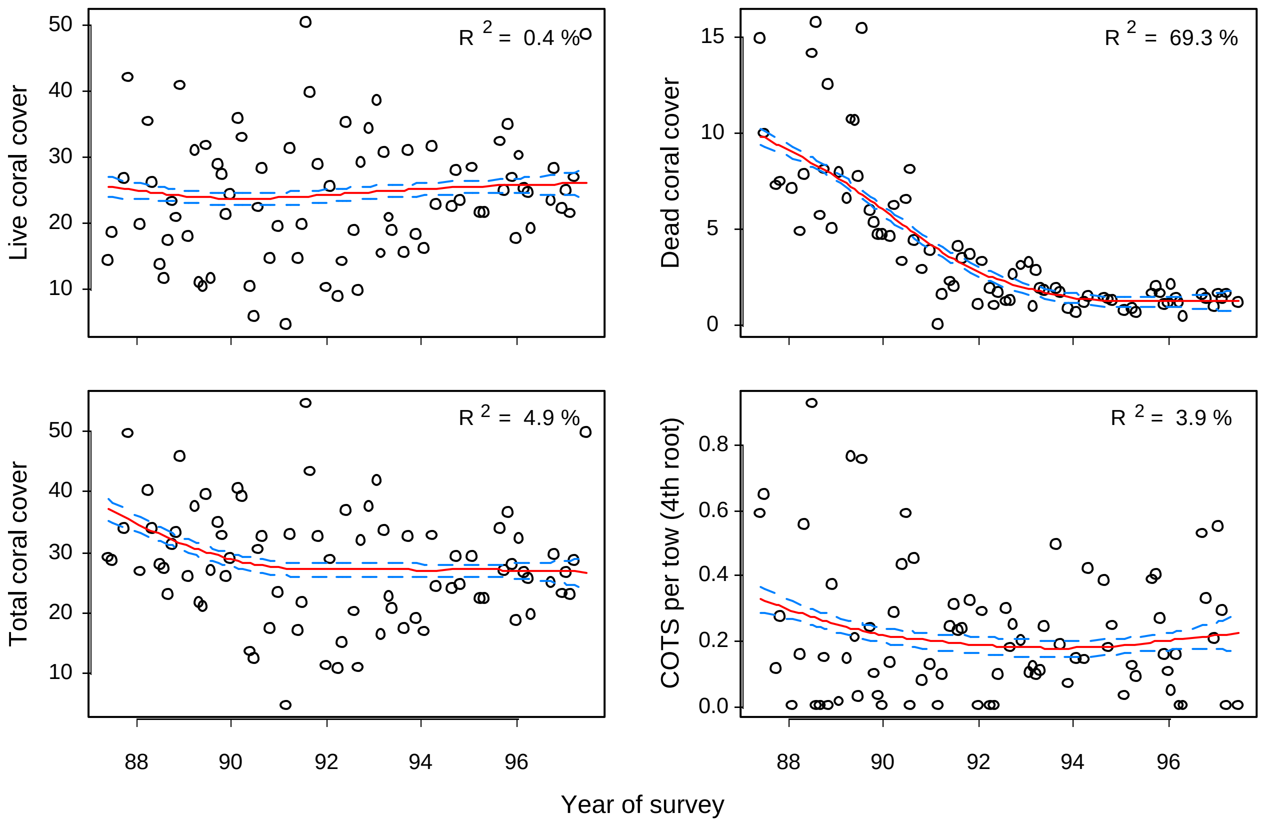


Figure 10. Trends in live and dead coral cover and COTS per tow (all fourth root transformed) and reef averaged for the period 1986-2000.

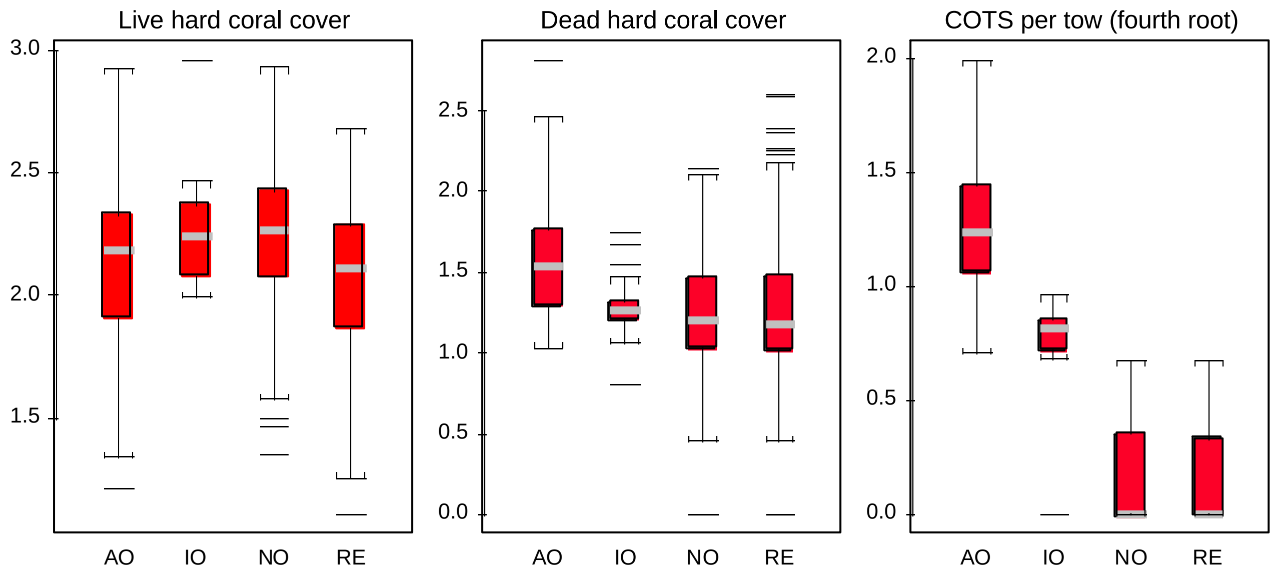


Figure 11. The distribution of mean live and dead coral and COTS per tow (fourth root) by the four status groups (AO, IO, NO, RE). The small differences between NO and RE reefs raises the question as to the validity of their current definition.

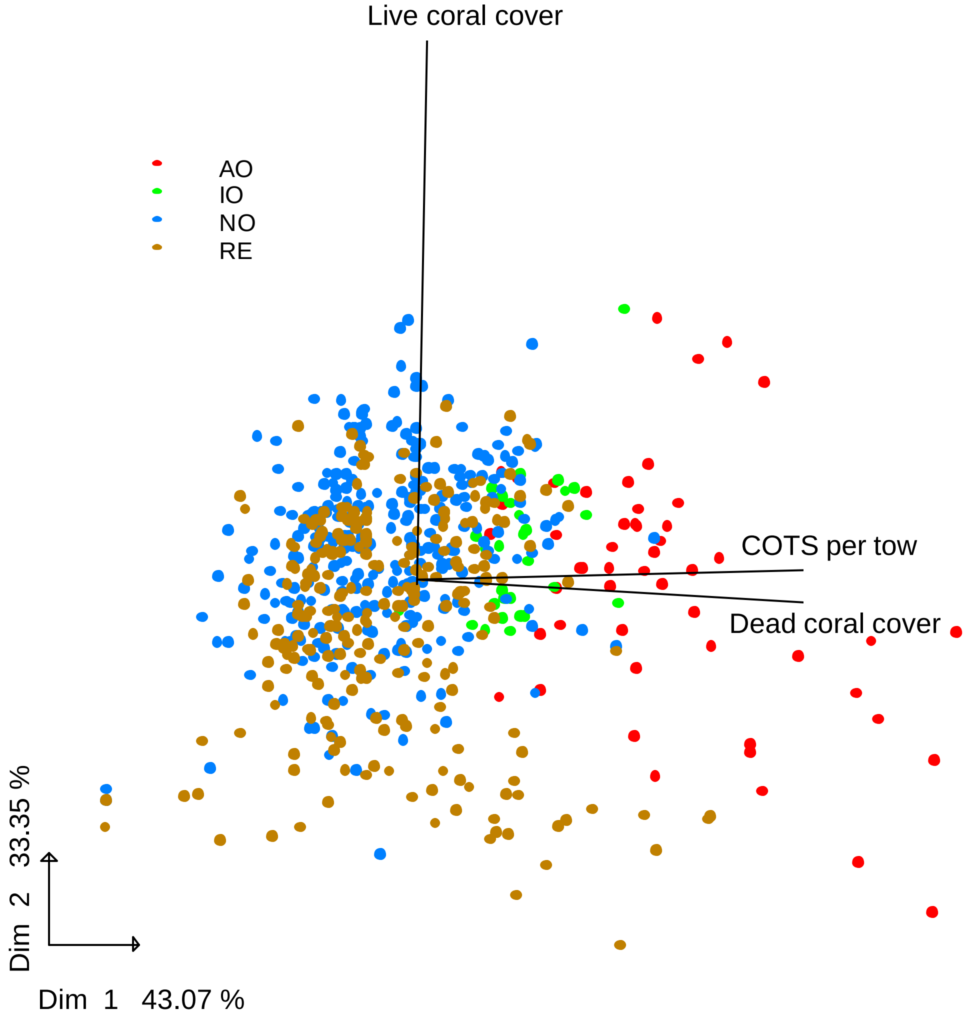


Figure 12. Biplot showing the distribution of mean live and dead coral (square root) and COTS per tow (fourth root) by the four status groups (AO, IO, NO, RE). The difference between NO and RE reefs is small.

Objective 1: PREDICTION OF COTS OUTBREAKS AND OTHER CHARACTERISTICS USING FINE-SCALE SURVEY DATA AND MANTA TOW SURVEY DATA

Predictions Using The Fine-Scale Survey Data

The use of FSS has been advocated as a method of detecting incipient outbreaks, thereby increasing the potential for effective intervention and control. The rationale for this is that large numbers of juveniles and at least moderate levels of hard coral cover on a reef will lead to outbreaks in subsequent years as the juveniles become mature adults. For FSS to be used in this way, the data from surveys of juveniles and / or immature must reliably predict mature numbers in subsequent years. We investigate this below, and also attempt to predict hard coral cover and the occurrences of active outbreaks.

Predicting immatures from juveniles

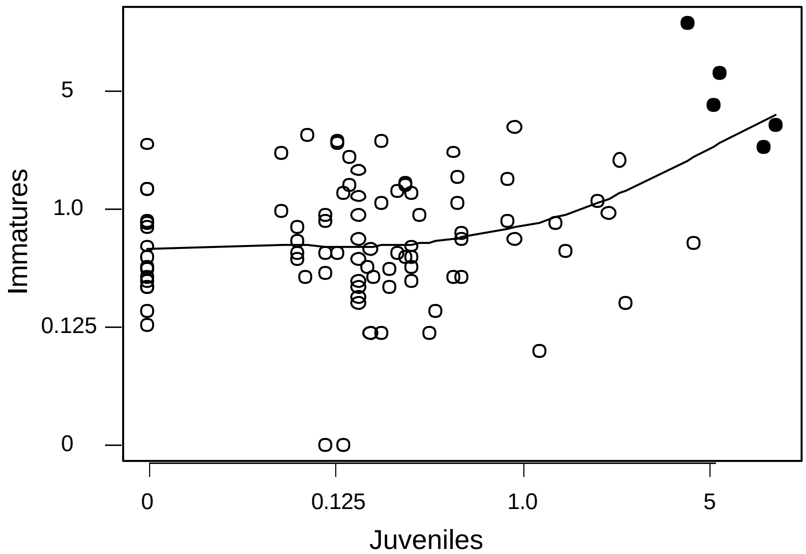


Figure 13. The relationship between reef-averaged immature and juvenile COTS (both fourth root transformed) from the preceding year. Only 5 points (filled in top right) from year 99-00 suggest a weak nonlinear trend.

A smoothed regression of immature abundances on lagged (i.e. the year before) juvenile abundances (both fourth root transformed) was marginally significant (Fig. 13) and explained 10.5% of the immature variance. Under cross-validation, the model had a cross-validated relative error (CVRE) of 0.94 (i.e. we could expect this model to predict 6% of the variance of immatures). Thus, from these data, lagged juvenile abundance is a poor predictor of immature abundance. Using additional lagged variables failed to improve the model.

For mature abundances regressed on immature abundances the model explained 21.7% of the variance (Fig. 14) and the CVRE was 0.84 (predicting 16%). Addition of live hard coral cover improved the model and prediction to 29.1% explained and 21.1% predictable, with matures increasing slightly with increasing previous live hard coral cover.

The relationships for individual years for both immature and mature adults (omitted) showed no systematic differences.

Predicting matures from immatures

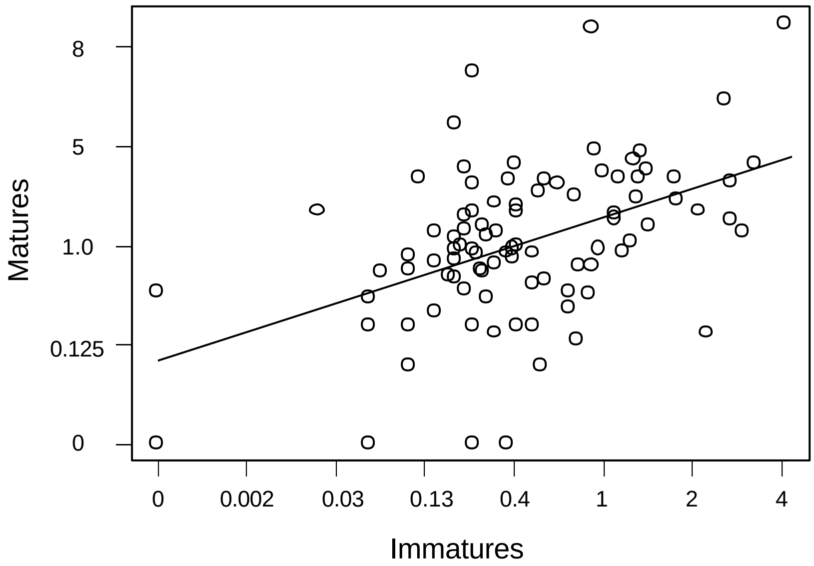


Figure 14. The relationship between reef-averaged mature and immature COTS (both fourth root transformed) from the preceding year (a). A moderate linear trend is shown (R^2 = 0.21). This relationship predicts 16% of variation in mature abundances.

Finding the best predictor of matures

Various models were used to find the best predictor of matures.

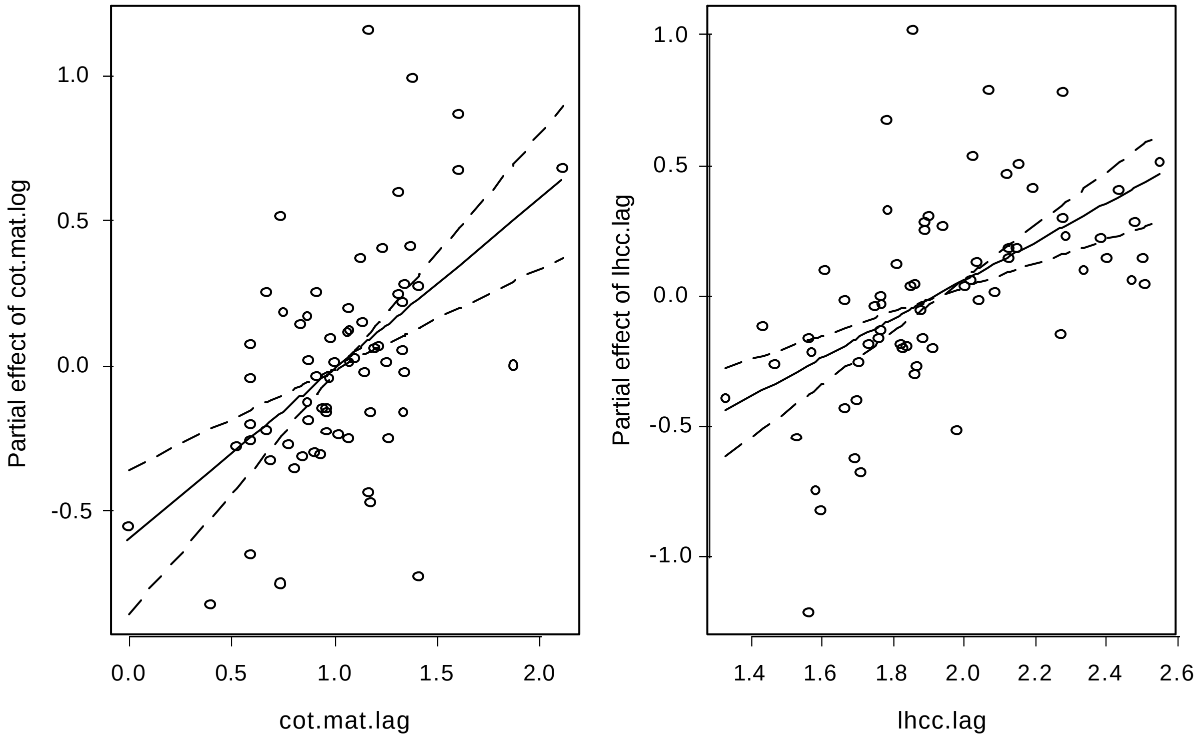


Figure 15. The prediction of matures from previous matures and previous live hard coral cover. The explanatory and predictive performance of the model are R^2 = 0.32 and predictive error of 0.79 (predicts 21%), with the partial effects plots show positive relationships between matures COTS and both previous mature COTS previous and live hard coral cover.

Predicting live hard coral cover from previous other data

The hard coral data was incomplete with 29% of observations missing. Various models were used to predict live hard coral cover from previous year's data. Live hard coral cover was weakly related to previous hard coral cover, but this relationship had very power predictive capacity (CVRE = 0.92; predictive capacity = 8%). As might be expected, if a reef was currently experiencing an active outbreak, then predicted coral cover was lower than non-outbreaking reefs.

Regression tree models were also used to explore the relationships and the predictability of matures, immature and coral cover from previous year's information. The models typically suggested a predictability of < 10% in agreement with the linear regressions. Thus we conclude that accurate prediction of populations of mature and immature COTS and hard coral cover is not possible from these data.

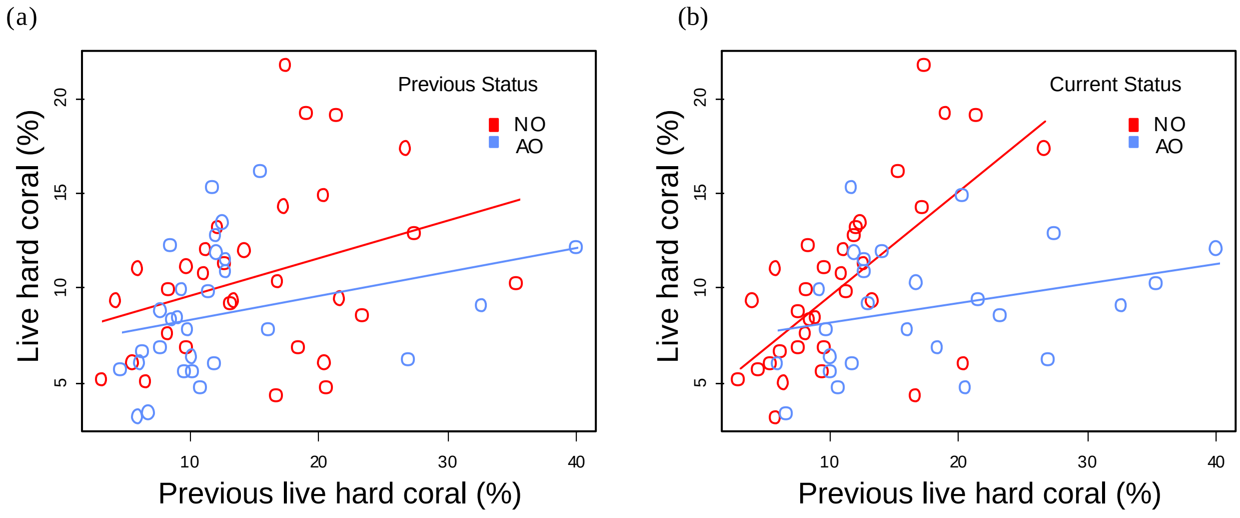


Figure 15. The relationships between current and previous hard coral cover. In (a) the groups are previous statuses, and there are no differences between groups with the regression explaining 14% of the variance. In (b) the current status defines the groups and the reduction in hard coral is strongly evident for currently outbreaking reefs. The two-line regression model explains 36% of variation. Prediction of hard coral is thus limited.

Predicting outbreaks from previous data

We have defined an FSS active outbreak at the level at > 1.0 mature adult COTS per 250 sq m transect averaged over the reef. Assuming FSS find all COTS, this is equivalent to 4000 per sq km, and coincides with the density of calibrated MT counts at 1 COT per tow (the area of the tow is ~ 2000 sq m).

The current and previous statuses of 92 reefs are shown below.

		Previous status	
		AO (51)	NO (41)
Current	AO (47)	33	14
status	NO (45)	18	27

Classification trees were used to assess the predictability of reef status from the previous year's data. The explanatory variables were numbers of COTS (all, juveniles, immature and matures), live coral cover and reef status. This was done for all reefs, and then for only reefs that were previously non-outbreaking. The latter is the critical management situation, since anticipating a new outbreak is the transition of interest.
The details of the analyses are included in the legends of Figures 16 and 17.

For all reefs, the error rate for predictions was estimated as 24%, a halving of the error rate compared to informed guessing (49% down to 24%), and is a reduction of 11% (35% down to 24%) compared to the status quo model (AO remains AO, and NO remains NO). Reefs with previously high numbers of immature (> 0.98 per transect) were high risk, as were reefs lower in immature (< 0.98 per transect), but high in live hard coral cover (> 10%) and high in total COTS (> 0.73 per transect).

For previously non-outbreaking reefs, the error rate for predictions was estimated as 23%, representing a 12% improvement on the status quo model, which in this case is the same as informed guessing. Reefs with previously high levels of live hard coral cover (> 13%) and higher levels of mature COTS (> 0.28 per transect) had increased risk, as did reefs with previously high levels of live hard coral cover (> 13%) but low levels of matures (< 0.28 per transect) and high levels of juveniles (< 0.23 per transect).

These levels of prediction are modest, but the interpretation of the models is useful. Subsidiary analyses showed that even when live hard coral cover is moderately low or higher (> 13%) and the numbers of COTS are reasonably high (~ 0.3 COTS per transect), then the odds of an outbreak being occurring on a non-outbreaking reef are in the range of 5 - 9 times higher.

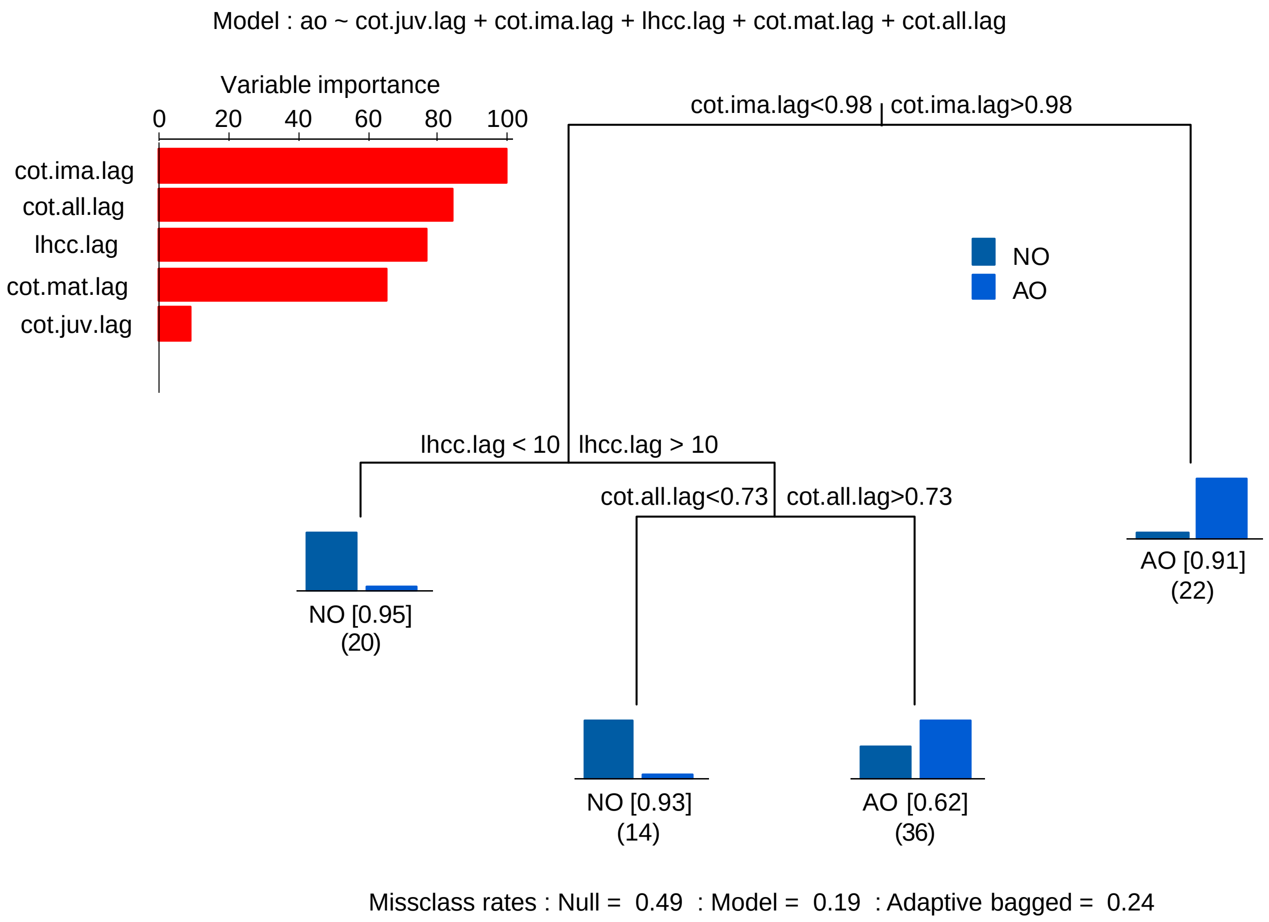


Figure 16. Classification tree explaining and predicting the status of reefs from fine-scale survey data. The response variable (ao) is the status of a reef as either outbreaking (AO) or non-outbreaking (NO). The explanatory variables are from the previous survey of the reef, and comprise the mean numbers of COTS (all COTS [cot.all.lag], juveniles [cot.juv.lag], immature [cot.ima.lag] and matures [cot.mat.lag]), the live hard coral cover [lhcc.lag] and the outbreak status [ao.lag]. The three splits of the tree are based on immature COTS, live coral cover and total COTS, with these three variables also best explaining status (ao) throughout the tree (see variable importance plot). The terminal nodes are labelled with their predicted type (AO or NO), the probability of reefs being that type (e.g. [0.95]), and the number of reefs. Overall the model has a misclassification rate of 19%. Observed error rates such as this are typically over-optimistic estimates of the true error (how well a model predicts) and we can obtain a better estimate using cross-validation. Under adaptive bagging (which uses cross-validation) the error rate was estimated as 24%.

Predictions Using Manta Tow Data

Predicting coral cover

Live and dead hard coral cover was strongly related to previous levels of cover, with a lesser but significant effect of previous reef status.

Live hard coral cover

The linear model with previous cover and different intercepts and same slopes for the three groups explained 56.6% of the variance (Fig. 18). The CVRE was 0.42 suggesting the model can usefully predict mean coral cover for a reef. The predicted cover was 4-10% lower if the previous status was AO, IO compared to NO and RE reefs which were similar.

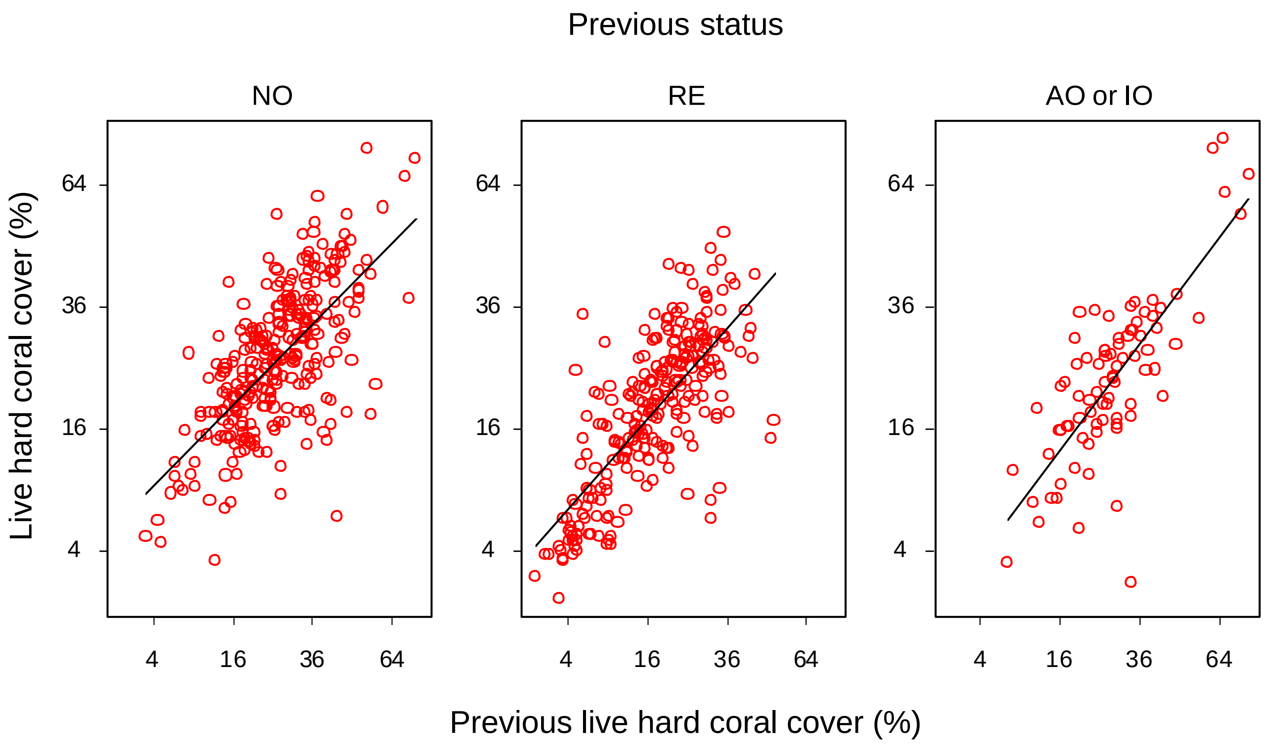
Dead hard coral cover

The linear model with previous cover and different intercepts and same slopes for the three groups explained 57.8% of the variance (Fig. 19). The CVRE was 0.40 suggesting the model can usefully predict mean coral cover for a reef. The predicted cover was 2-4% lower if the previous status was AO, IO compared to NO and RE reefs which were similar. The results are strikingly similar to those for mean live cover, but as would be expected the effect of AO, IO *vs.* NO and RE reefs is opposite.

Predicting COTS per tow for reefs from previous data from the same reef

A regression tree was used to predict COTS per tow. The number of COTS per tow increased strongly with the previous number of COTS, and for high levels of COTS (> 0.82) further increased with high levels of previous live and dead coral. The tree explained 51% of COTS variation, with a predictive error of 0.56. This compares favourably with FSS predictions of matures which had predictive error of 0.79. However, this comparison is across different data sets from different reefs that have different ranges of COTS. To account for the different ranges of data, a subset of the MT data was selected to have approximately the same distribution of COTS counts as the FSS data. The regression tree was rerun and a tree similar to the analysis of the full data set resulted (omitted). This model explained 48% of COTS variation, with a predictive error of 0.60. This can be interpreted as MT surveys can predict COTS from previous survey data twice as accurately as FSS. There are several qualifiers to this statement, namely we are assuming: (1) COTS seen in MT surveys are equivalent to ‘FSS matures’, and (2) differences in locations of reefs and years of surveys do not affect the relationships used to model predictability.

(a)



(b)

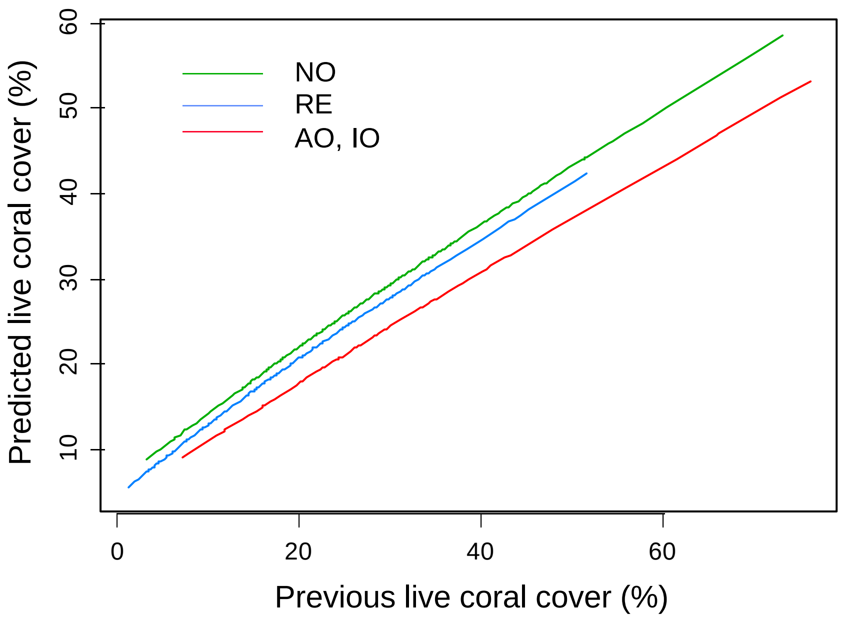
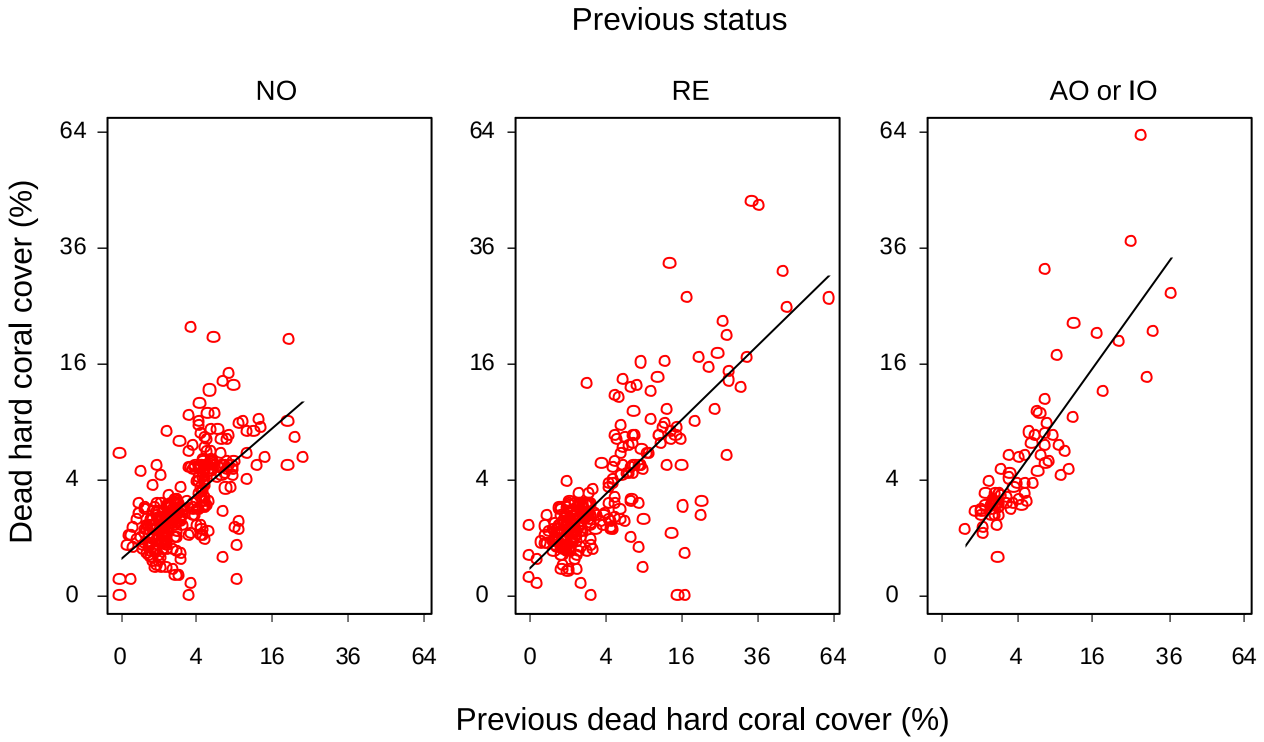


Figure 18. Plots (a) of live coral cover against previous (within 3 months - 2 years) live coral cover (both square root). For all three previous status groups (NO, RE and AO-IO) moderately strong linear relationships are shown. In (b) the predicted values (back transformed) are shown for the three status groups.

(a)



(b)

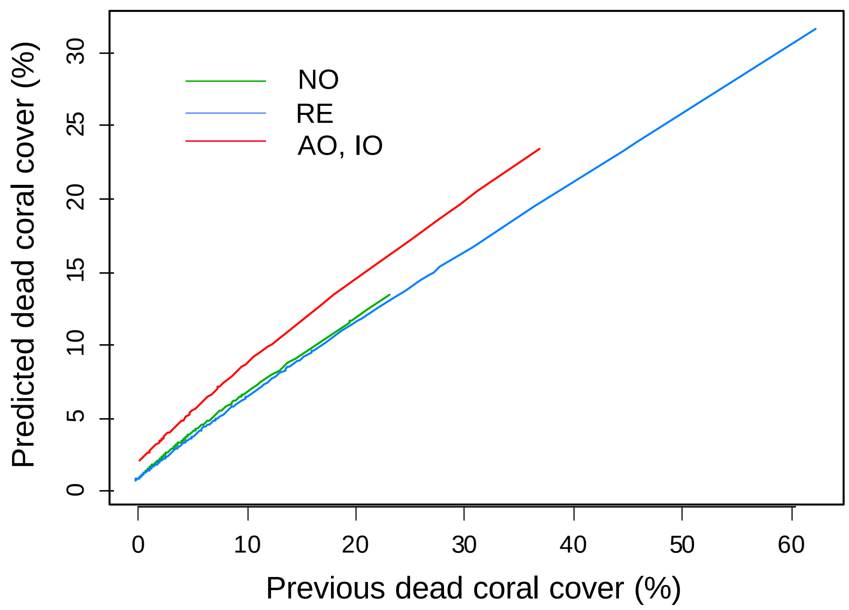


Figure 19. Plots (a) of dead coral cover against previous (within 3 months - 2 years) dead coral cover (both square root). For all three previous status groups (NO, RE and AO-IO) moderately strong linear relationships are shown. In (b) the predicted values (back transformed) are shown for the three status groups.

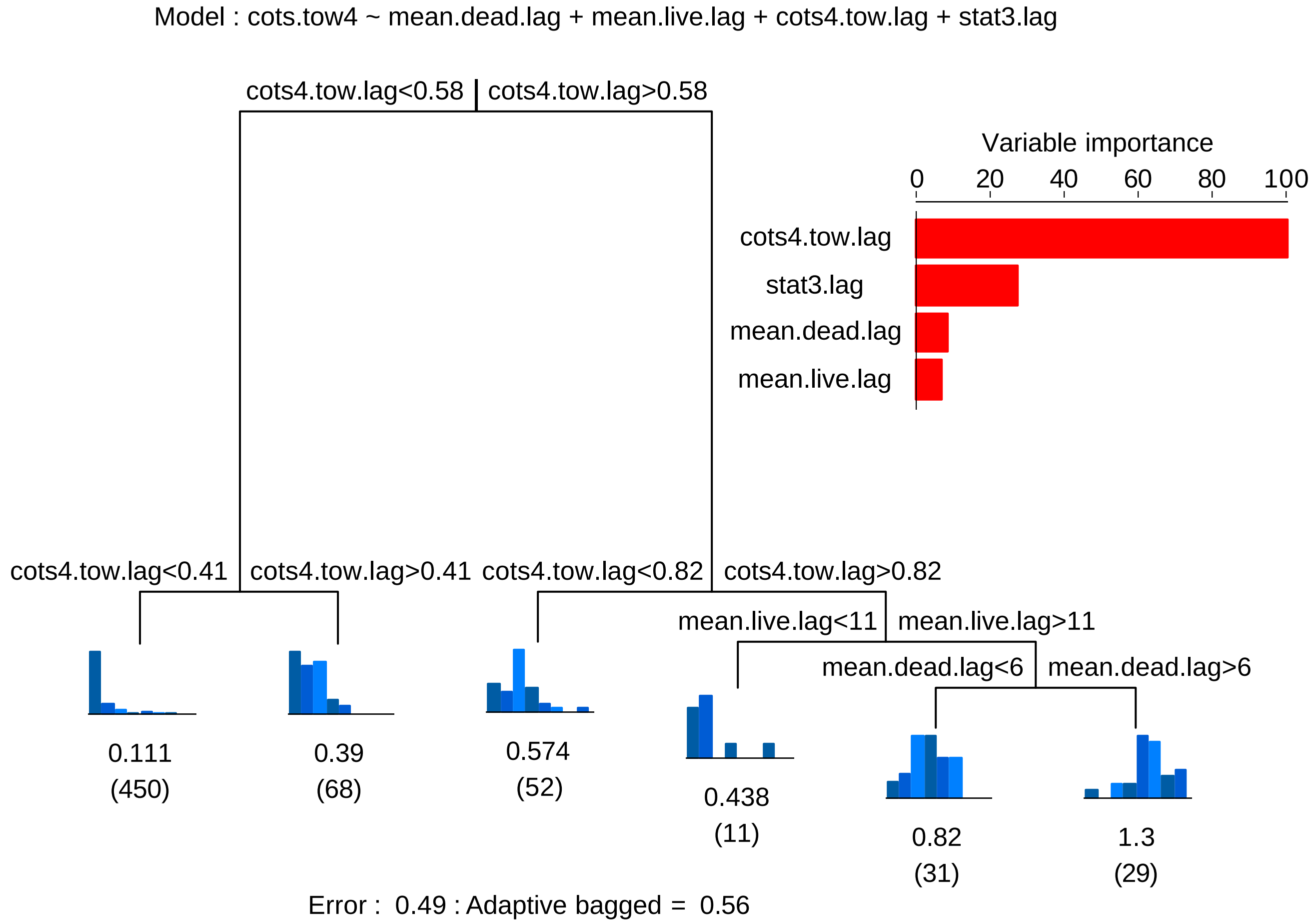


Figure 20. The regression tree shows current COTS (fourth root) best explained by previous COTS, with, at high levels of COTS, increasing numbers where live and dead coral are high.

Predicting status of reefs from previous data from the same reef

The MT reef status (active outbreak = AO, incipient outbreak = IO, recovery = RE, non-outbreak = NO) is defined in a complex manner dependent on live and dead coral cover and the history of the reefs status (see Appendix Two). This retrospective change of reef status precludes these estimates of reef status to be used predictively. For the purposes of prediction, we have defined MT outbreaks as > 0.1 COTS per tow. This level was used since it is our best estimate of equivalent densities (in this case 4000 per sq km) from data common to MT and FSS (see section on comparison of common data).

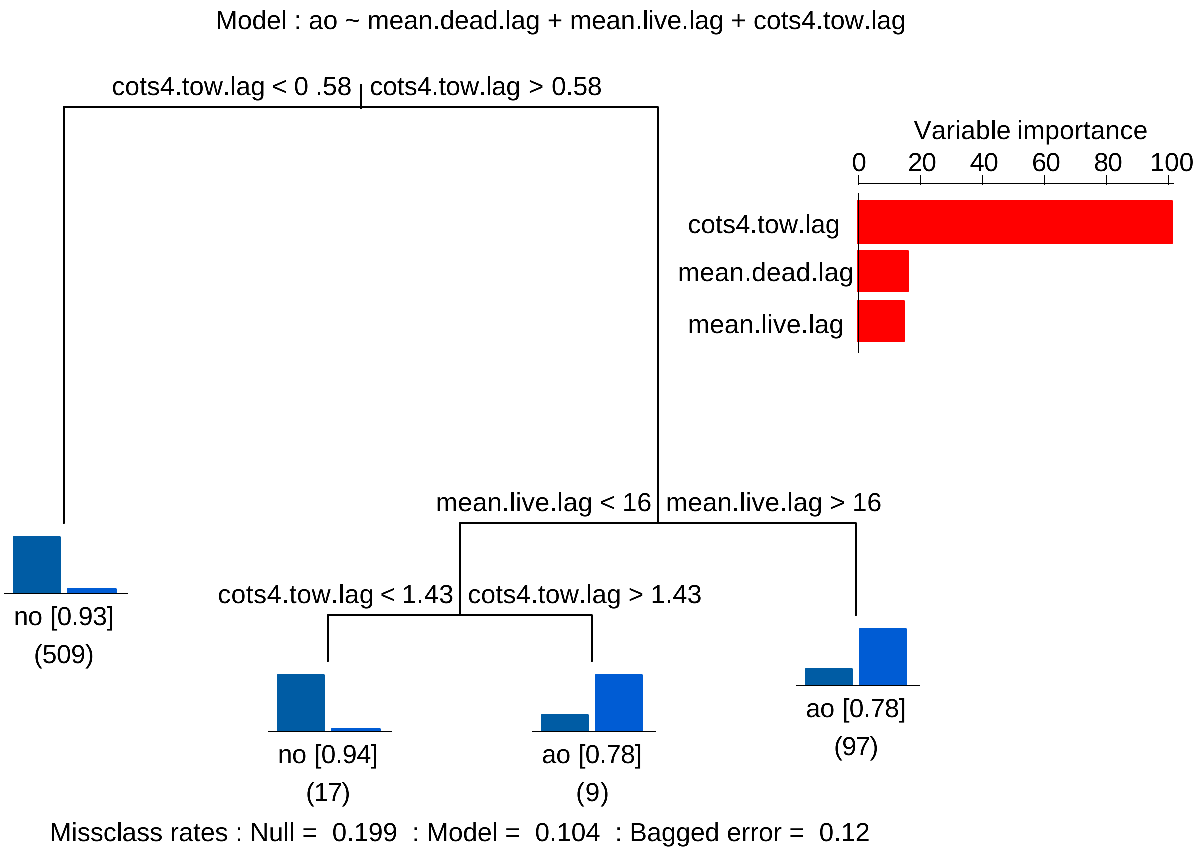


Figure 21. Predicting reef status (ao, no) from manta tow data. The predictors of the models are based on the previous number of COTS per tow and previous hard coral cover. The tree defines two low-risk and two high risk groups, The two low risk groups on the left of the tree (with risk of outbreak 0.07 and 0.06) are either low in previous COTS per tow (<0.11) or have moderate to high previous COTS per tow (0.11 - 4.2) but low previous mean live coral cover (<16%). The two high risk groups (both with risk 0.78) are: (1) either moderate to severe previous COTS per tow (>0.11) and moderate to high previous mean live coral cover (>16%), and (2) severe previous COTS per tow (>4.2) but low previous mean live coral cover (<16%).

The classification tree analysis (Fig. 21) effectively predicts status with a 10.4% misclassification error rate; the estimated error rate for using these four classifications is 12.0%. This compares favourably with the predictions based on FSS with its predicted error rate of 24.0%. However, the ranges and number of data are quite different, and favour the MT classification.

In order to make a fair comparison, a subset of the MT data was selected such that the range of predictor variables was as similar as possible (in particular the COTS counts). The proportion of outbreaking reefs to be predicted was also similar to the FSS data; 47% (MT) *vs.* 49% (FSS). A new classification tree was grown from these data, and as would be expected its performance was less than for the full data. The model had a misclassification error rate of 17.2% and the predicted error rate was 18.2%, still substantially lower than the FSS classification (24%). The structure of the tree changed little compared to the full data (Fig. 21).

Objective 2: COMPARISON OF FINE-SCALE AND MANTA TOW SURVEYS ON COMMON REEFS.

The reefs in common to FSS and MT for the period 94-95 through to 99-00 are shown in Figure 22. There were 66 FSS reef-year surveys and 59 FSS reef-year surveys. Of the 66 FSS surveys, 27 (41%) were outbreaking, whereas of the 59 MT surveys, 11 (3 AO and 8 IO) (19%) were outbreaking. In 34 instances reefs were surveyed by FSS and MT in the same year. The proportions of outbreaks for common reef-years were 12 (35%) for FSS and 6 for (18%) for MT.

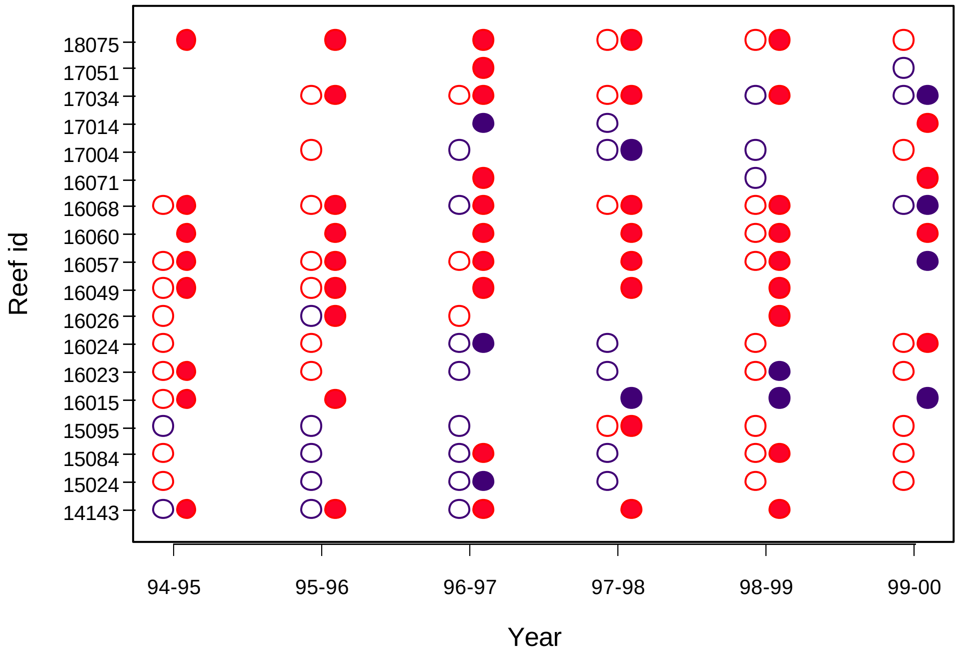


Figure 22. Reefs in common to the FSS and MT for the period 94-95 through to 99-00. Red and blue points indicate NO and AO (AO-IO for MT) respectively, and open and closed circles indicate FSS and MT respectively.

The trends in changes in COTS and live coral cover from FSS and MT were consistent (Figures 23 and 24).

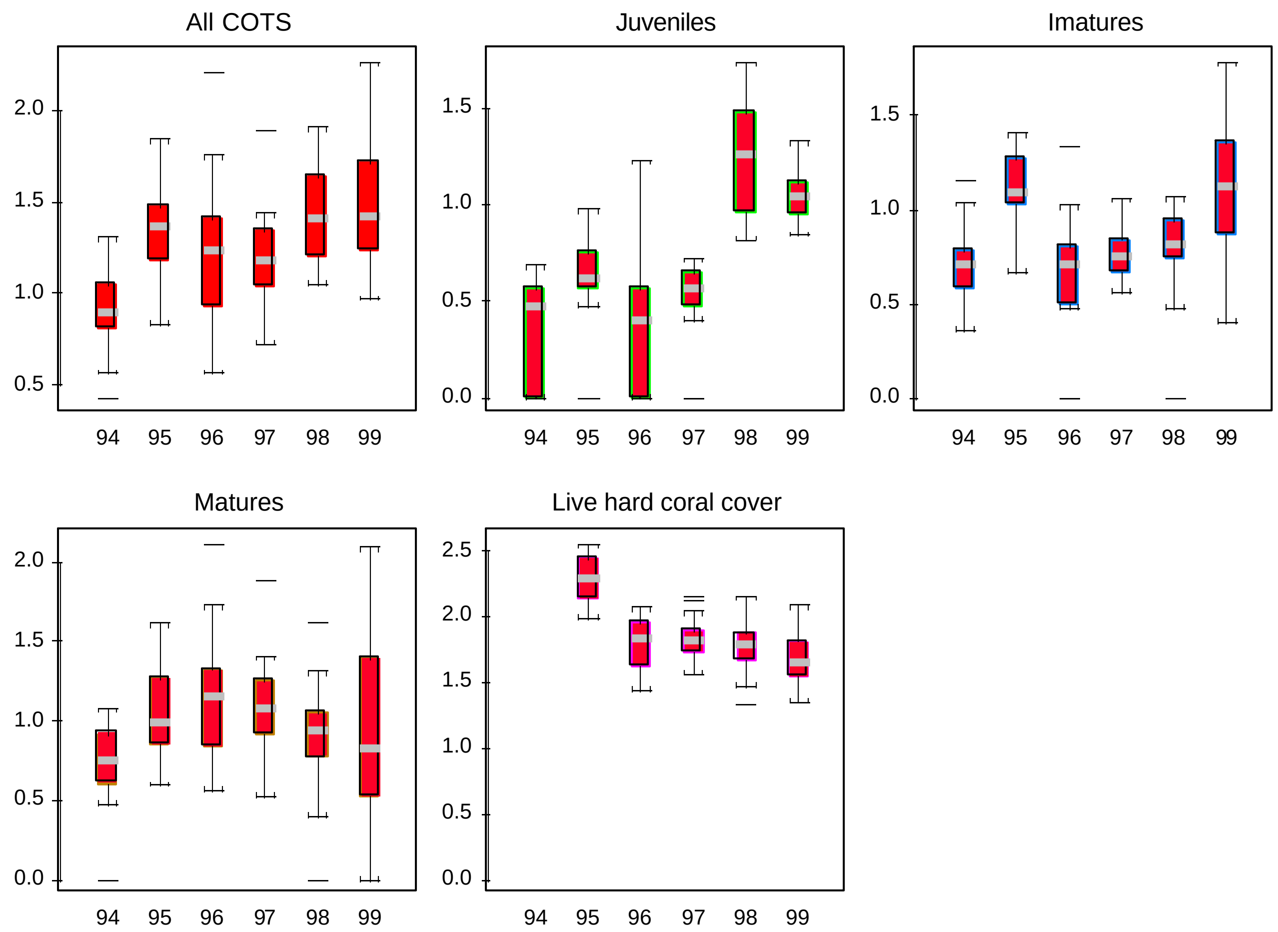


Figure 23. Distributions of COTS and live hard coral cover of 66 FSS reefs for the period 94-95 to 99-00. The mean COTS (fourth root) show a steady increase over time, largely due to increase in juveniles in the last two years. Live hard coral cover declines over the same period.

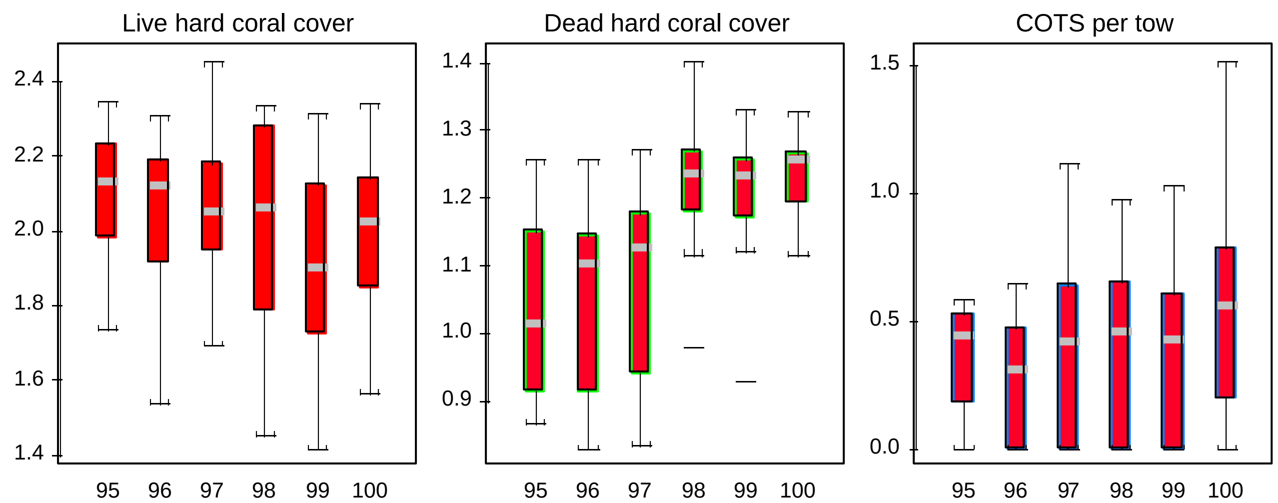


Figure 24. Distributions of live and dead hard coral cover and COTS of 59 MT reefs for the period 94-95 to 99-00. The mean COTS (fourth root) show a small increase over time. Live hard coral cover (fourth root) declines and dead coral cover (fourth root) increases over the same period.

Redefining Reef Status

The following points suggest we need to adjust MT outbreak criteria.

1. On common reef-years, FSS give higher estimates of mature adults compared to calibrated manta tow estimates by a factor of approximately 2.76 (95% CI = 2.37, 4.48). This is a conservative estimate of the undercounting since it based on calibration of reef means, and calibration from the individual counts would give lower estimates of COTS; possibly by ~ 10-40%. The differences in counts are possibly due to: (a) under-estimation by manta tows due to factors such as narrowed search path and / or reduced attention, (b) inaccuracy of the calibrations, and (c) FSS transects being located in areas favouring COTS
2. FSS also declare twice the rate of outbreaking reefs on common reef-years.
3. For MT outbreaking reefs (all data with >7 surveys) both AO and IO showed substantial declines in hard coral cover.
4. IO refers to incipient outbreaks, yet only 3 of 36 IOs become AO; the rest become NO or RE or remain as IO. Incipient is clearly an inappropriate description.

AO and IO are levels which are experiencing high COTS numbers. If calibrations are correct then >1500 per sq km (~ 0.22 COTS per tow); if the FSS - MT correction is applied then >4200 per sq km.
With a level of 0.1 COTS per tow the respective levels are 1100 and 2800, and, for the common data, the number of outbreaks agrees.

Recommendation 1: REEFS WITH LEVELS OF COTS > 0.22 PER TOW SHOULD CLASSIFIED AS ACTIVE OUTBREAKS (AO) [perhaps > 1 COT per tow = SEVERE OUTBREAK (SO)]

Recommendation 2: REEFS WITH LEVELS OF COTS > 0.1 PER TOW SHOULD CLASSIFIED AS POTENTIAL OUTBREAKS (PO) [or perhaps MARGINAL OUTBREAKS (MO)].

The new MT ratings would be less severe than FSS current criteria, but would lead to approximately 50% more AOs and 40% more outbreaks (AO + PO) in total.

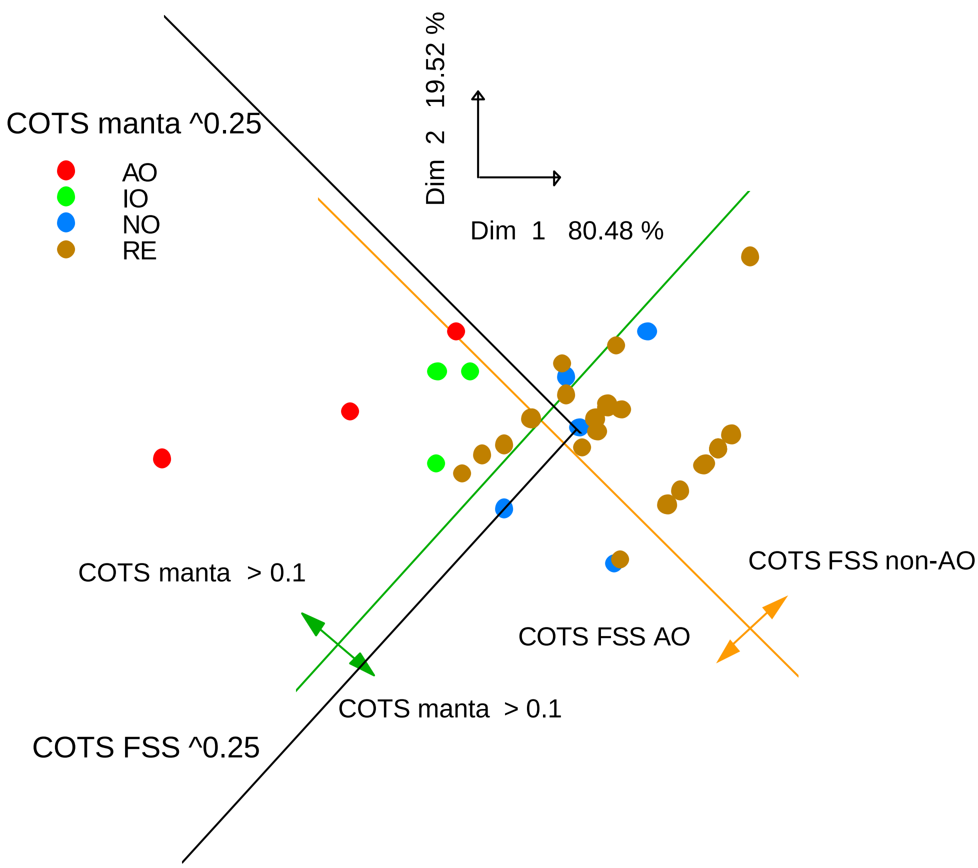


Figure 25. Biplot of COTS values (fourth root) for common FSS and MT reefs (n=34) for the period 94-95 to 99-00. The MT status (AO, IO, NO, RE) of reefs is shown. Points with FSS AO status (FSS COTS > 1) are shown to the lower left of the orange line. The green line indicates the proposed level (MT COTS > 0.1) fro declaring outbreaks (see also Tables 1 and 2). The common variance (a measure of agreement of FSS and MT COTS values) is 80.48%.

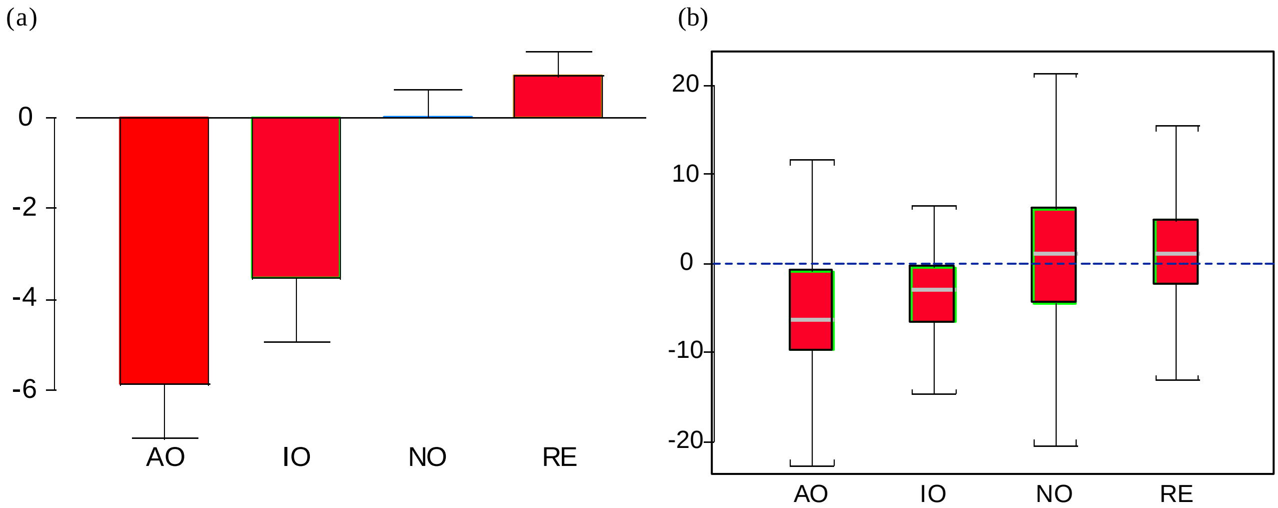


Figure 26. Changes in hard coral for status of reef (AO, IO, NO, RE). For AO and IO there are consistent declines (~ 6% and 4% respectively), with >75% declining in each category.

Table 1. Cross-classification of FSS and MT status of 34 common reefs.

		MT status			
		AO	IO	NO	RE
FSS status	non AO	1	0	3	18
	AO	2	3	2	5

Table 2. Cross-classification of FSS and MT status of 34 common reefs with categories of MT status.

		MT status		
		AO > 0.22	PO > 0.1	NO-RE
FSS status	non AO	1	2	19
	AO	5	4	3

Objective 3: SPATIAL PATTERNS OF OUTBREAKS

The Spatial Pattern of Outbreaks from the Manta Tow Surveys

Predicting the characteristics of a reef from its previous data has been shown to have potential. However, there is possibly information to be gained which improves prediction by considering broader spatial scale to include near-neighbours and larger patterns and movements of outbreaks. The pattern of two earlier outbreaks has been documented (Moran and De'ath etc) and the movement of outbreaks has been related to currents (Black et al). Looking at the manta tow data for the period 1983-current (Fig. 27), we see three outbreaks of duration > 8 years. These comprise: (a) a fixed ongoing (1985-current) outbreak of moderate intensity in the Swains (~22.5° S), (b) an intense outbreak (1983-1991) with slight southward movement (~20° S), and (c) a rapidly moving outbreak (1992-current) moving south from 12° S to 18° S.

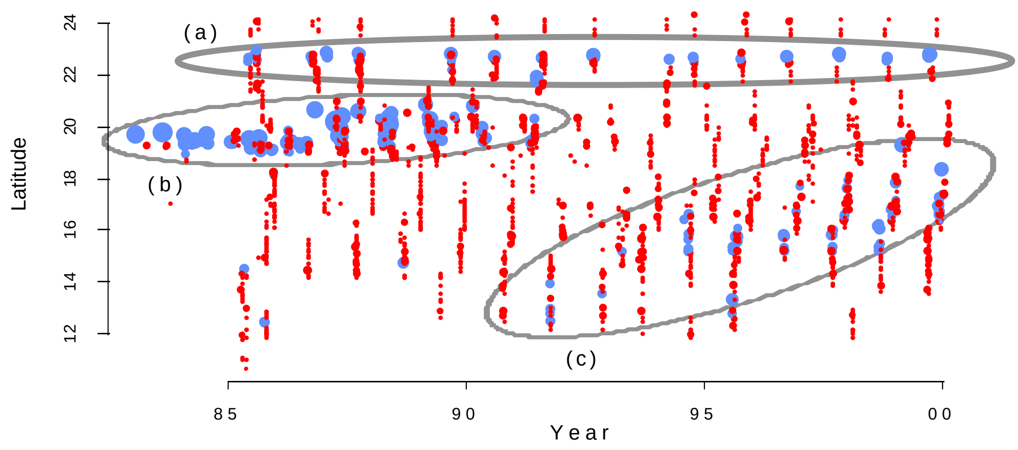


Figure 27. Movement of outbreaks from manta tow records. Blue point denote outbreaking (AO or IO) reefs and red points denote non-outbreaking reefs (NO or RE). Point size is proportional to 4th root of COTS abundance. Three 'sets' of outbreaks are apparent: (a) a fixed ongoing (1985-current) outbreak of moderate intensity in the Swains (~22.5° S), (b) an intense outbreak (1983-1991) with slight southward movement (~20° S), and (c) a rapidly moving outbreak (1992-current) moving south from 12° S to 18° S.

These patterns have implications for using spatial data for improving our reef predictions based only on previous history of the same reef. For example, if we knew we were in a static outbreak (a) or southern drift (b), then we could select the appropriate spatial information to enhance the predictions. However we cannot be sure of such broad patterns until several years after they are established. Thus we have to rely on more general methods; the obvious candidate is to use previous data from near neighbours and previous data from the reef for which we wish to predict.

Comparison of fine-scale and manta tow surveys for the current southern wave.

The movement of the current wave is revealed by both the fine-scale (94-current) and manta tow surveys (91-current). For both methods the sampling effort moves south with the wave and any estimates should be adjusted for this effect. The estimated rates of movement for the two methods are similar, in the range (0.25 - 4° per year).

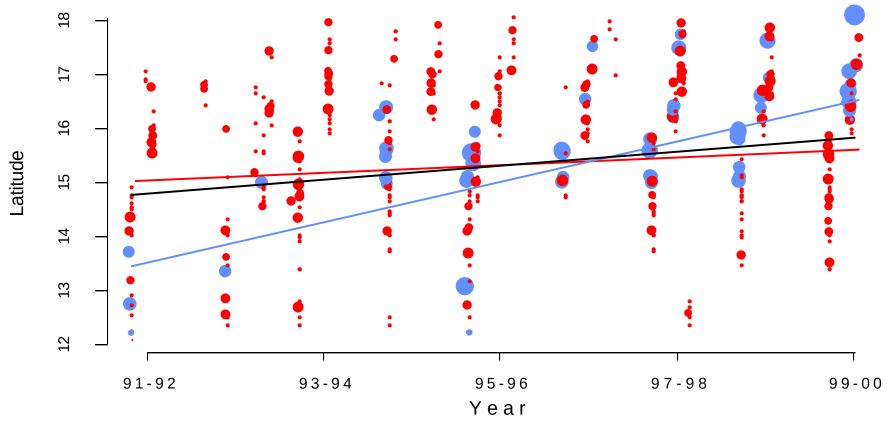


Figure 28. Manta tow data showing the southern moving outbreak (1992-2000). The blue line estimates the linear trend of the latitudinal centroid for each year, and similarly the red and black lines estimate the centroid for non-outbreaking and all reefs respectively. The slope of the black lines show the sampling effort has shifted south over time and this should be corrected for in any estimate of the spatial movement of the outbreaks.

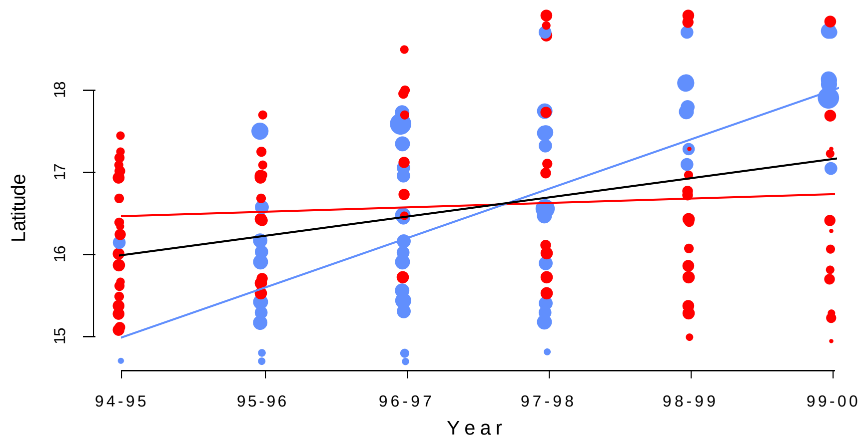


Figure 29. Fine-scale survey data showing the southern moving outbreak (1992-2000) for the period 1994-95 to 1999-00. The lines are as for Figure 25. The estimated rate of southern drift is similar to that derived from the manta tow data.

Objective 4: FINE-SCALE SURVEYS: SAMPLING INTENSITY AND FURTHER INFORMATION ON SPATIAL AND TEMPORAL CHANGE

The data for these analyses are a balanced subset of all the FSS data, comprising 8 reefs, each with 2 zones (front and back), 10 sites within each zone, and 3 years of observations (97-98, 98-99 and 99-00). Reefs, years and zone were treated as fixed effects, and sites as random. Sites were nested in the crossing of reefs, zones and years since they were relaid each year at each reef. The data were analysed for all COTS, matures, immature and juveniles by ANOVA and MANOVA, and components of variance were calculated for sites with reef by zone by year and for sampling error (the mean square residual error).

The effects are strongly significant for all factors and interactions. The zone, year and zone by year effects are strongest, though for all COTS the year effect is weaker. These results are consistent with: (1) the shift of juvenile and immature starfish across the age cohorts, and the death of adults, (2) the favouring of fronts of reefs by juveniles, and the backs of reefs by matures, and (3) the high mobility of starfish as they search for coral prey. The strong zone effects, coupled with the known aggregative behaviour of starfish, once more reinforce the necessity of reef-wide searches. In this context, it is possible that the lack of predictability of cohorts (size-classes) across years is due in part to searching only part of the front and backs of reefs, and not whole reefs.

The components of variance indicate relatively small transect variance within sites. Given the highly aggregative nature of COTS, it is likely that distances between transects within sites were not an order of magnitude greater than distances between sites. The precision of alternative sampling schemes is shown in Figure 30. Dependent of the costs of transects *vs.* sites, reductions to 5 sites each of 2 transects, or to 10 sites with single transects are worthy of consideration.

Matures, immature and juveniles (MANOVA)

Term	Df	Pillai Trace	approx. F	Num Df	Den Df
reef.id	8	0.38	9.01	24	1458
zone	1	0.32	76.11	3	484
year	2	0.71	88.57	6	970
reef.id:zone	8	0.17	3.75	24	1458
reef.id:year	16	0.63	8.17	48	1458
zone:year	2	0.18	16.79	6	970
reef.id:zone:year	16	0.18	1.98	48	1458
residuals	486				

Matures

Term	Df	SS	MS	F
reef.id	8	19.03	2.38	8.4
zone	1	19.26	19.26	68.7
year	2	61.93	30.96	110.5
reef.id:zone	8	10.12	1.26	4.5
reef.id:year	16	66.04	4.13	14.7
zone:year	2	6.60	3.30	11.8
reef.id:zone:year	16	11.56	0.72	2.6
site in reef.id:zone:year	486	136.09	0.28	
residuals	540	72.74	0.13	

Immature

Term	Df	SS	MS	F
reef.id	8	20.21	2.52	8.6
zone	1	4.77	4.76	16.2
year	2	48.20	24.10	81.8
reef.id:zone	8	7.74	0.96	3.2
reef.id:year	16	40.20	2.51	8.5
zone:year	2	13.87	6.93	23.5
reef.id:zone:year	16	8.03	0.50	1.7
site in reef.id:zone:year	486	143.14	0.29	
residuals	540	110.85	0.20	

Juveniles

Term	Df	SS	MS	F
reef.id	8	22.03	2.75	9.0
zone	1	50.27	50.27	164.9
year	2	80.98	40.4	132.8
reef.id:zone	8	7.51	0.93	3.0
reef.id:year	16	22.02	1.37	4.5
zone:year	2	15.93	7.96	26.1
reef.id:zone:year	16	11.48	0.71	2.3
site in reef.id:zone:year	486	148.08	0.30	
residuals	540	81.20	0.15	

All COTS

Term	Df	SS	MS	F
reef.id	8	26.96	3.37	8.4
zone	1	7.56	7.56	18.8
year	2	6.76	3.38	8.4
reef.id:zone	8	10.96	1.37	3.4
reef.id:year	16	82.80	5.17	12.9
zone:year	2	45.61	22.80	56.8
reef.id:zone:year	16	21.71	1.35	3.3
site in reef.id:zone:year	486	194.89	0.40	
Residuals	540	113.48	0.21	

Variance components

	Sites	Residuals
All COTS	0.095	0.210
Mature	0.073	0.135
Immature	0.045	0.205
Juvenile	0.077	0.150

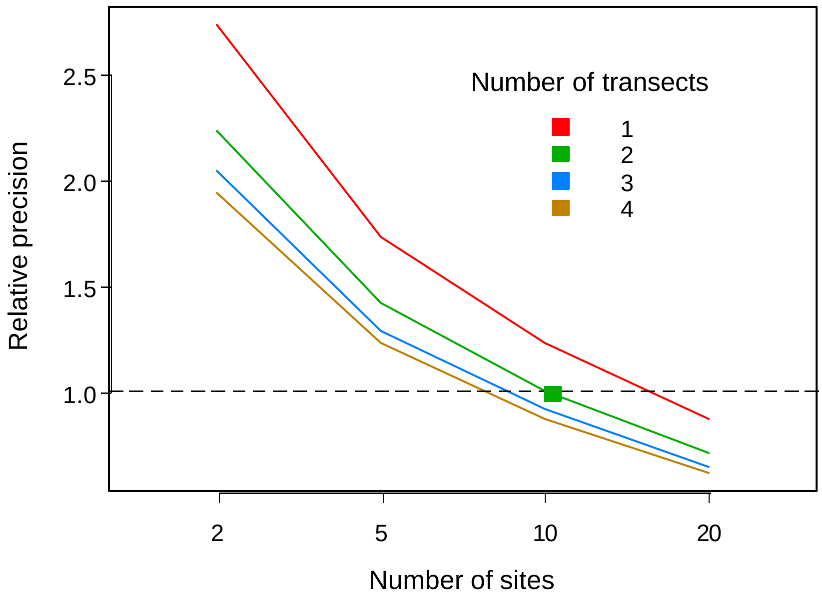


Figure 30. Relative precision as a function of the number of sites and number of transects for fine-scale surveys. Components of variance for transect variance within sites and error with transect were taken as 0.075 and 0.15, typical of the surveys. For the fine-scale surveys, 10 sites, each with 2 transects, were used, and the precision of other schemes relative to that setup are indicated.

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APPENDIX ONE -- DEFINITION OF REEF STATUS FROM MANTA TOW SURVEYS

To determine a reef's status in regards to COTS
The status can be one of the following

NO - no outbreak
RE - Recovering from outbreak
IO - Incipent Outbreak
AO - Active Outbreak

IF previous status is AO then
mean_cots < 0.22 ➔ RE
otherwise ➔ AO

IF previous status is NO or this is the first Survey of this reef then
mean_cots < .22 ➔ NO
mean_cots >1 ➔ AO
otherwise ➔ IO

IF previous status is IO and before it was IO it was NO then
If mean_cots < 0.22
(If median_live <= median_live for previous occasion where status was NO
minus 2 AIMS categories ➔ RE
else ➔ NO)

mean_cots > ➔ AO
otherwise ➔ IO

IF previous is RE or (previous is IO and before it was IO it was RE or we do not know what it was before it was IO) then
mean_cots between .22 and 1 ➔ IO
mean_cots > 1 ➔ AO
mean_cots < .22 and
(
(status has been RE for 15 Years)
or
(median_live >= 4L)
or
(median_live >= ((median_live for previous occasion
where status was NO) + (2 AIMS categories)))
or
((median_live >= median_live for previous occasion
where status was NO) and has been for at least 2 Survey years.)

) ➔ NO
otherwise ➔ RE

That last part again in English:

If previous is RE and mean_cots < .22
a reef can be said to be recovered if one of the following is true.

- It has been recovering for 15 Years
- median_live >= 4L
- median_live has "over-shot" by at least 2 AIMS categories the point where it was before the outbreak.

- median_live has reached the point where it was before the outbreak and sustained that for at least 2 survey years

N.B. When considering median_live for previous occasion, all old AIMS categories (ie 1, 2 3, 4, 5 rather than 1L, 1U, 2L, 2U etc) and all split medians (2L / 3U) are rounded up. Unless it is a split old category (2 / 3) where the L subsection of the Higher part of the split is considered.

eg 2 becomes 2U
2U / 3L becomes 3L
2 / 3 becomes 3L

When considering median_live for current, all split categories are rounded down.

eg 2U / 3L becomes 2U

eg if median_live for previous occasion where status is NO is 2 then the 2U is taken to be median_live for previous occasion. So that reef is considered to be revovering untill one of th following is true:

1. it has been recovering for 15 years
2. median_live >= 4L (hard coded)
3. median_live >= 3U (2U + 2 AIMS categories)
4. median_live >= 2U for at least 2 survey years.

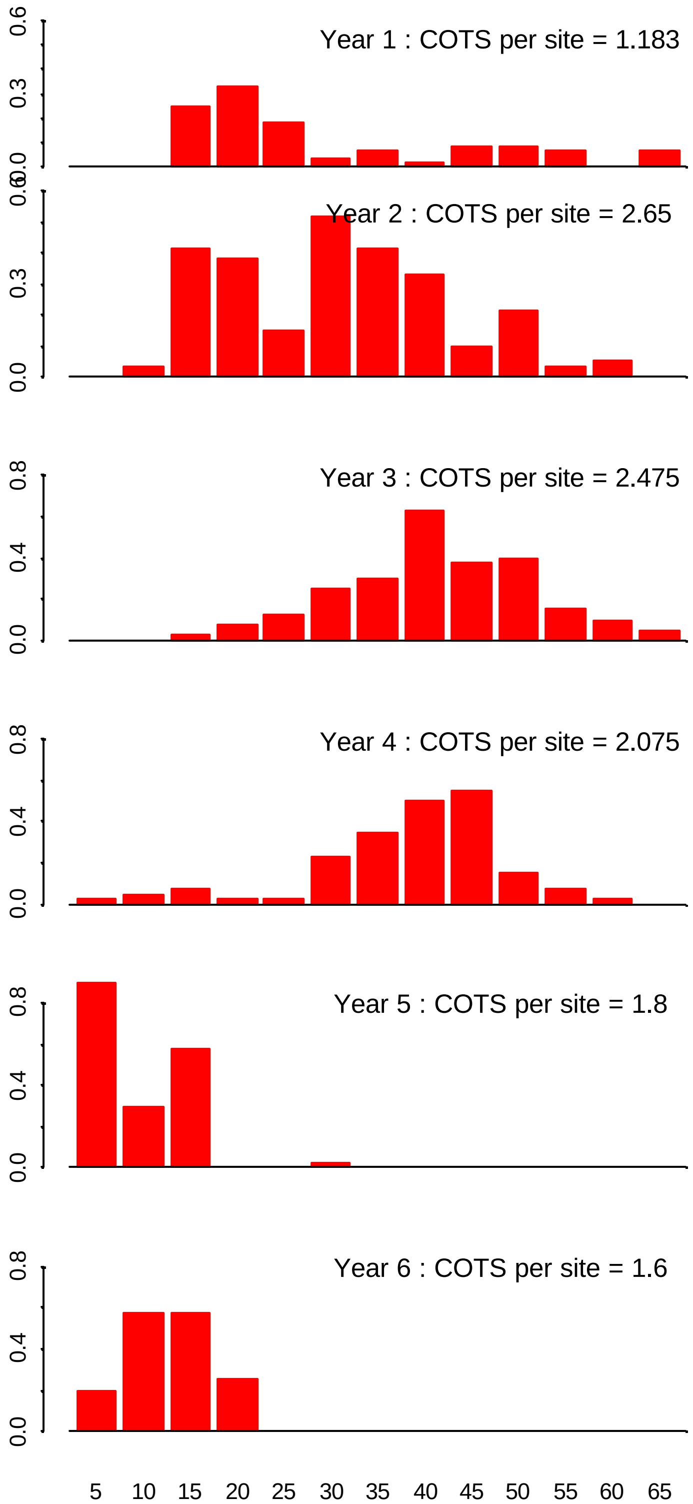
if median_live was 3L / 3U then this would be rounded down to 3L so condition 3 would not be satisfied.

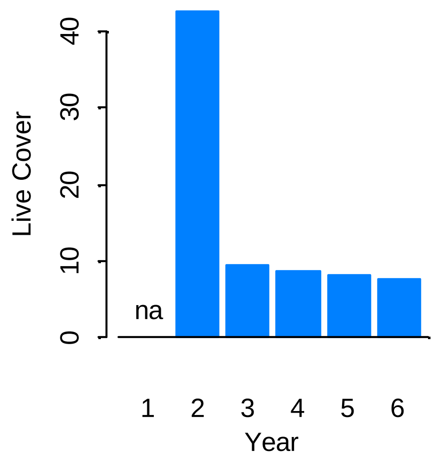
Only surveys with sample class of 'K', 'C', or 'G' are included in any calculations (ie "previous status", "previous occasion where status was NO", "sustained for at least 2 survey years" etc).

Note this algorithm assumes that for the first survey of a reef it is treated as previous status of NO. If there is previous history of COTS available then it is up to the discretion of the scientist to give that reef a status of RE.

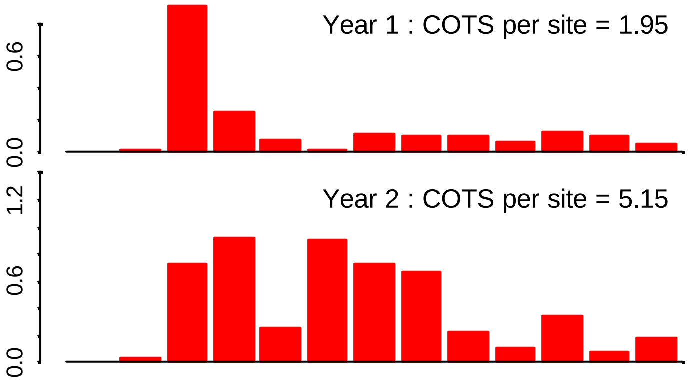
APPENDIX TWO -- SIZE FREQUENCY PLOTS OVER YEARS FOR ALL FINE-SCALE SURVEY REEFS WITH MORE THAN TWO VISITS

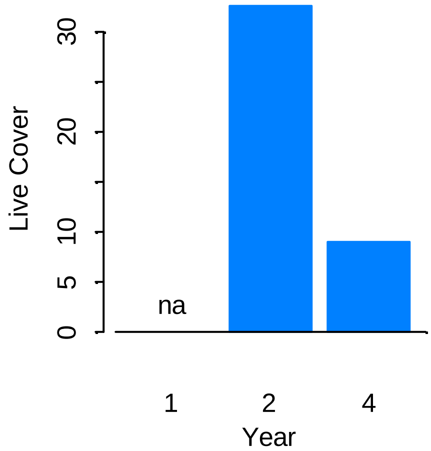
14132

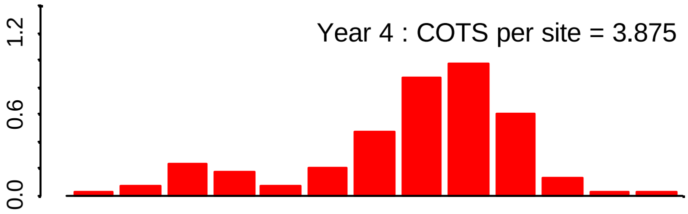




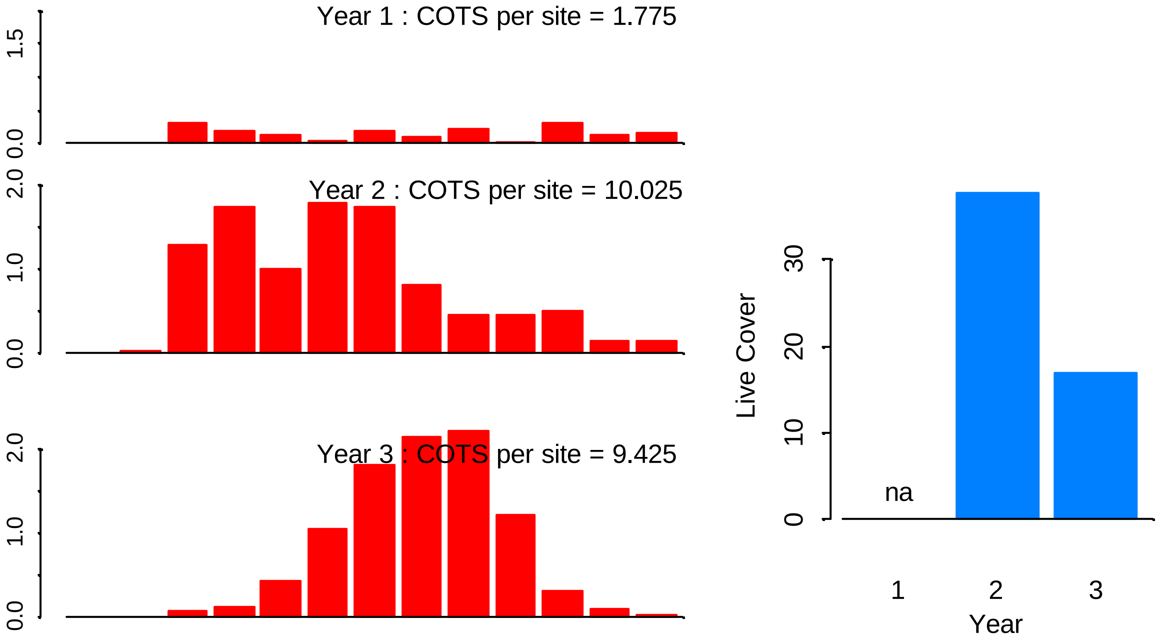
14133


Year 1 : COTS per site = 1.95
Year 2 : COTS per site = 5.15
0.6
0.0
1.2
0.6
0.0


Live Cover
30
20
10
5
0
na
1
2
4
Year

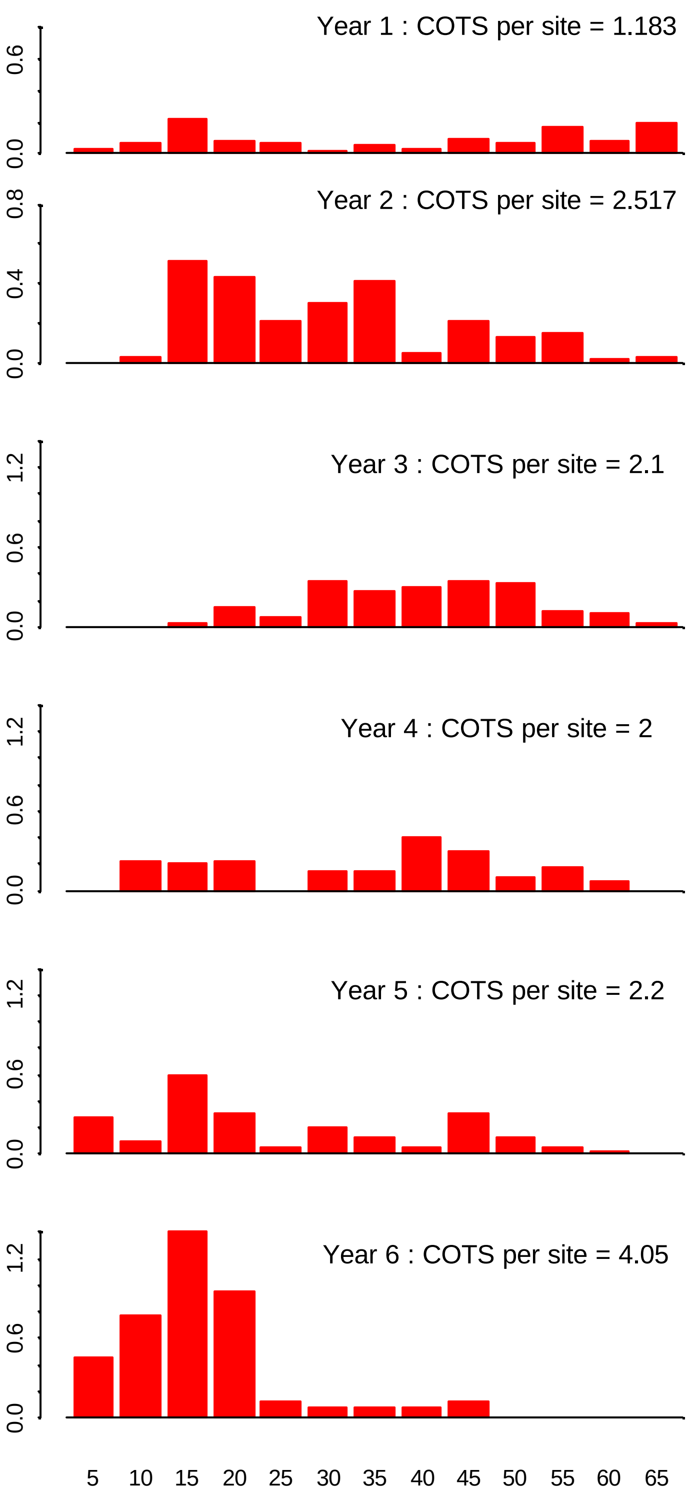

Year 4 : COTS per site = 3.875
1.2
0.6
0.0

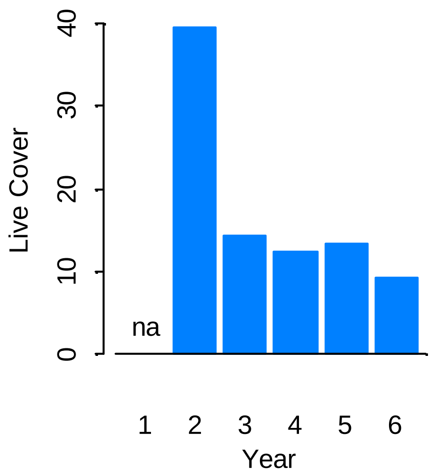
14143



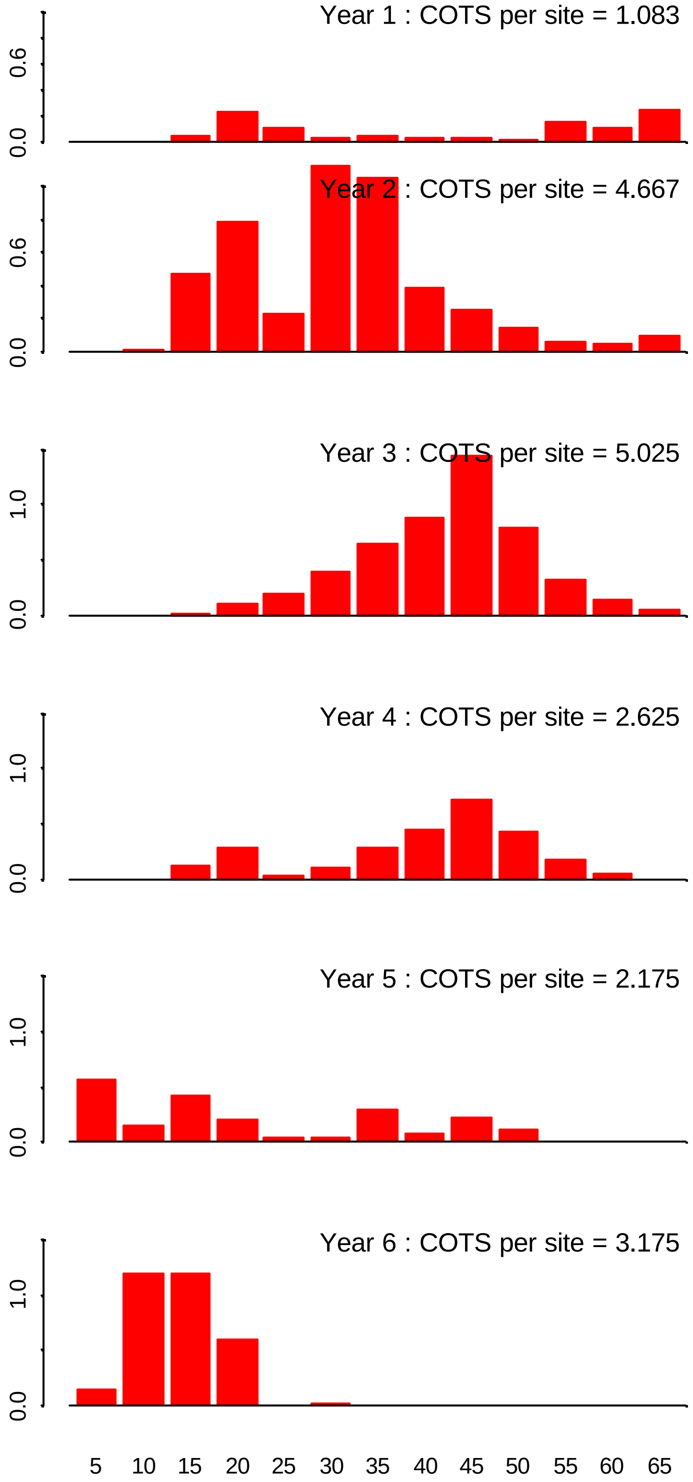
Year 1 : COTS per site = 1.775
Year 2 : COTS per site = 10.025
Year 3 : COTS per site = 9.425
0.0
1.5
0.0
1.0
2.0
0.0
1.0
2.0
Live Cover
0
10
20
30
na
1
2
3
Year

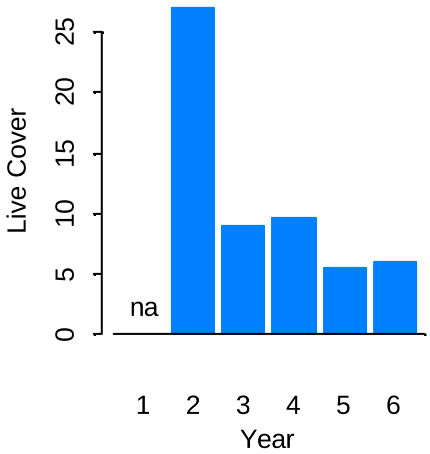
15019


Year 1 : COTS per site = 1.183
Year 2 : COTS per site = 2.517
Year 3 : COTS per site = 2.1
Year 4 : COTS per site = 2
Year 5 : COTS per site = 2.2
Year 6 : COTS per site = 4.05
0.0
0.6
0.4
0.8
1.2
5 10 15 20 25 30 35 40 45 50 55 60 65


Live Cover
0 10 20 30 40
na
1 2 3 4 5 6
Year

15024


Year 1 : COTS per site = 1.083
Year 2 : COTS per site = 4.667
Year 3 : COTS per site = 5.025
Year 4 : COTS per site = 2.625
Year 5 : COTS per site = 2.175
Year 6 : COTS per site = 3.175
0.0
0.6
1.0
5
10
15
20
25
30
35
40
45
50
55
60
65


Live Cover
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5
10
15
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25
na
1
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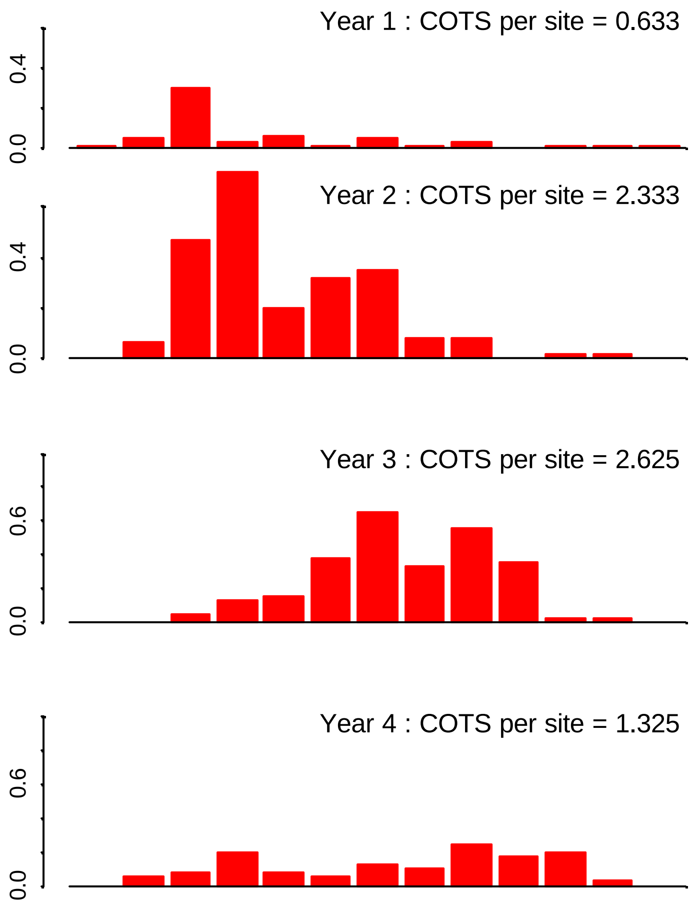
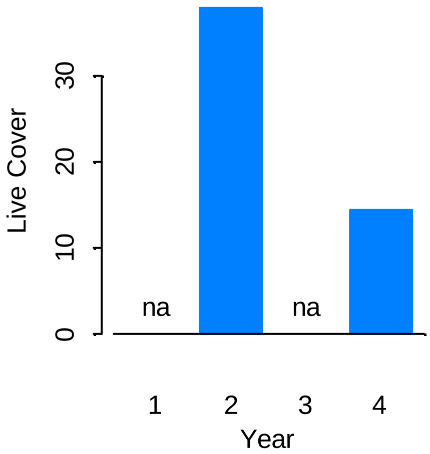
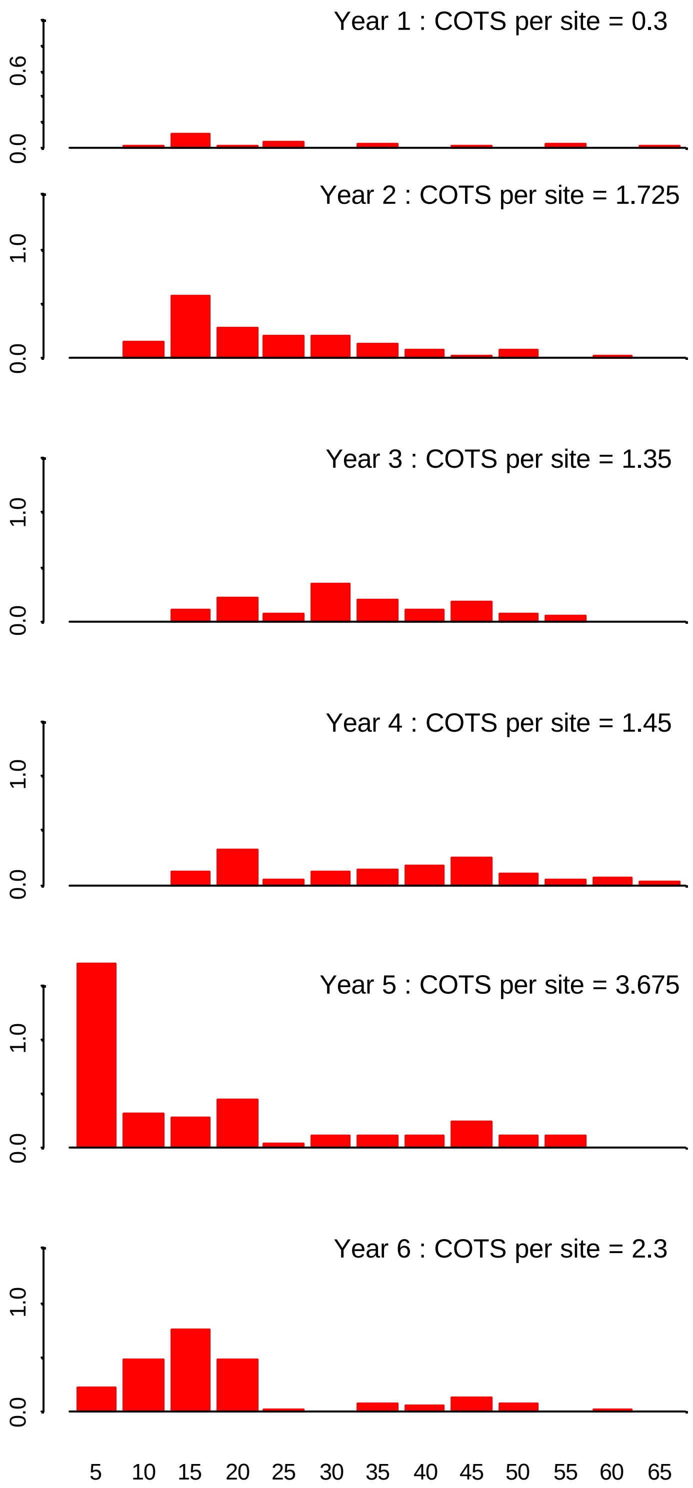
3
4
5
6
Year

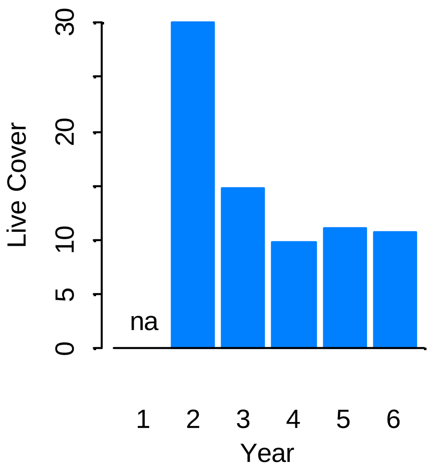
15033


Year 1 : COTS per site = 0.633
0.0
0.4
Year 2 : COTS per site = 2.333
0.0
0.4
Year 3 : COTS per site = 2.625
0.0
0.6
Year 4 : COTS per site = 1.325
0.0
0.6

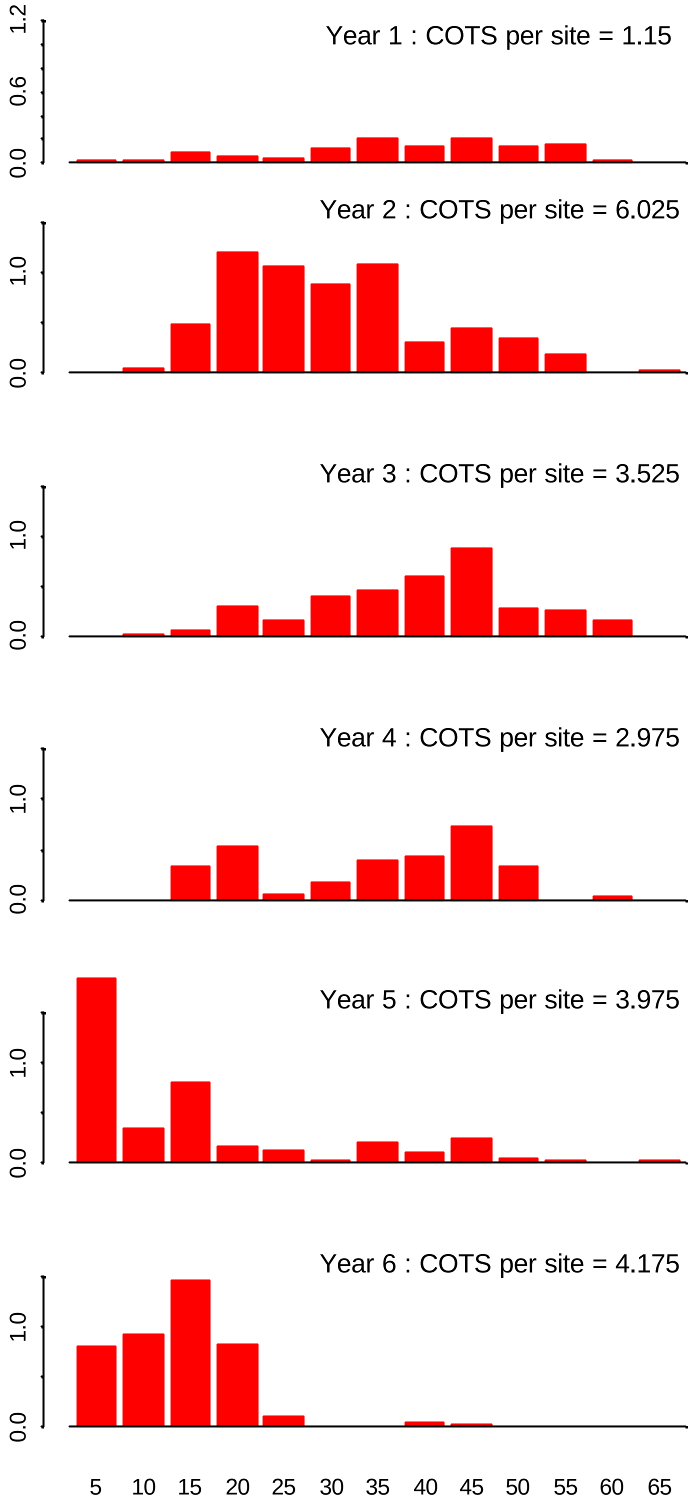

Live Cover
0
10
20
30
na
na
1
2
3
4
Year

15070

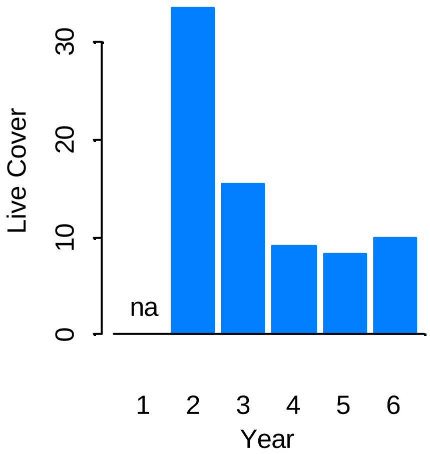

Year 1 : COTS per site = 0.3
Year 2 : COTS per site = 1.725
Year 3 : COTS per site = 1.35
Year 4 : COTS per site = 1.45
Year 5 : COTS per site = 3.675
Year 6 : COTS per site = 2.3
0.0
0.6
1.0
5
10
15
20
25
30
35
40
45
50
55
60
65


Live Cover
0
5
10
20
30
na
1
2
3
4
5
6
Year

15084



Year 1 : COTS per site = 1.15
Year 2 : COTS per site = 6.025
Year 3 : COTS per site = 3.525
Year 4 : COTS per site = 2.975
Year 5 : COTS per site = 3.975
Year 6 : COTS per site = 4.175
0.0
0.6
1.2
1.0
5
10
15
20
25
30
35
40
45
50
55
60
65



Live Cover
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10
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30
na
1
2
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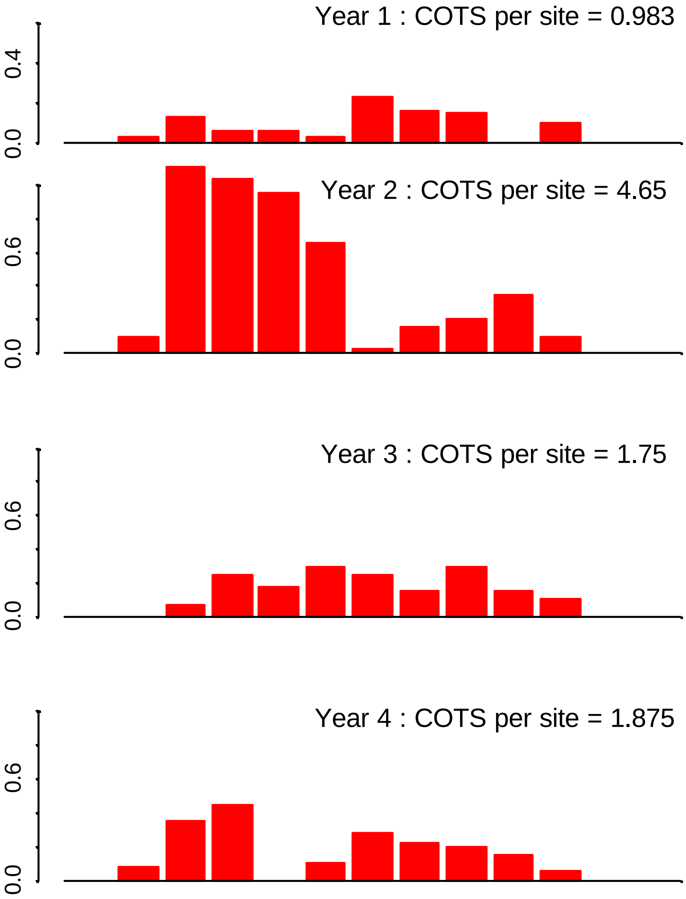
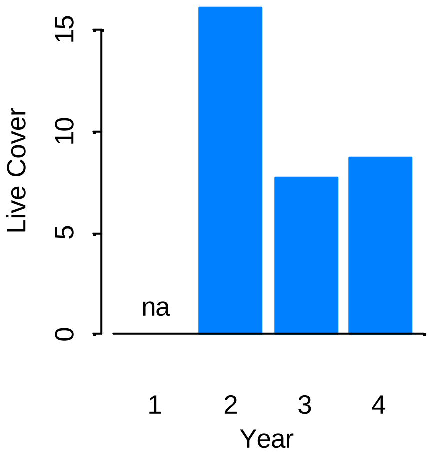
4
5
6
Year

15089


Year 1 : COTS per site = 0.983
0.0
0.4
Year 2 : COTS per site = 4.65
0.0
0.6
Year 3 : COTS per site = 1.75
0.0
0.6
Year 4 : COTS per site = 1.875
0.0
0.6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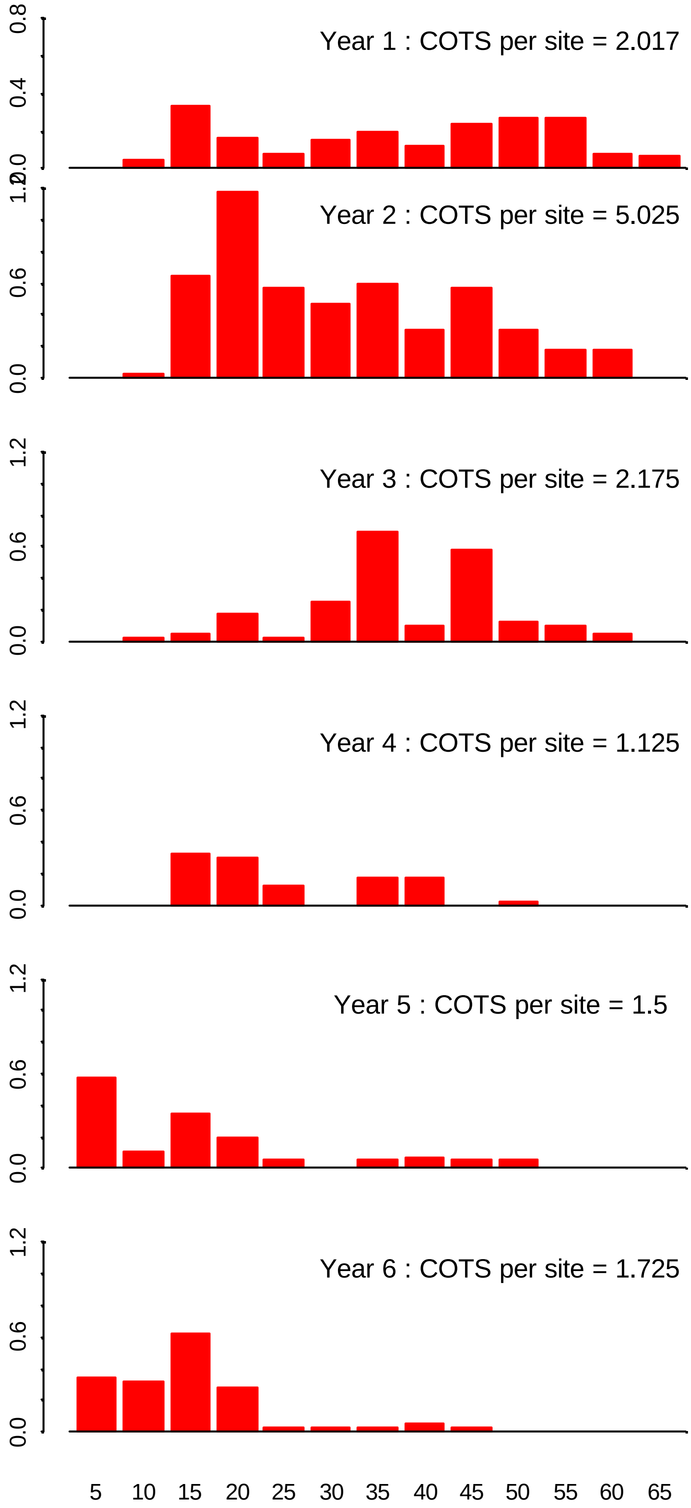
Year

15095


Year 1 : COTS per site = 2.017
Year 2 : COTS per site = 5.025
Year 3 : COTS per site = 2.175
Year 4 : COTS per site = 1.125
Year 5 : COTS per site = 1.5
Year 6 : COTS per site = 1.725
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0.4
0.8
0.6
1.2
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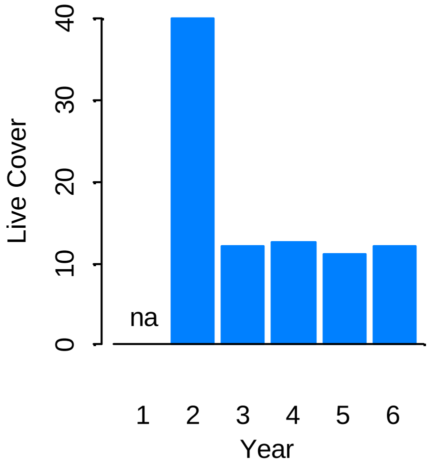
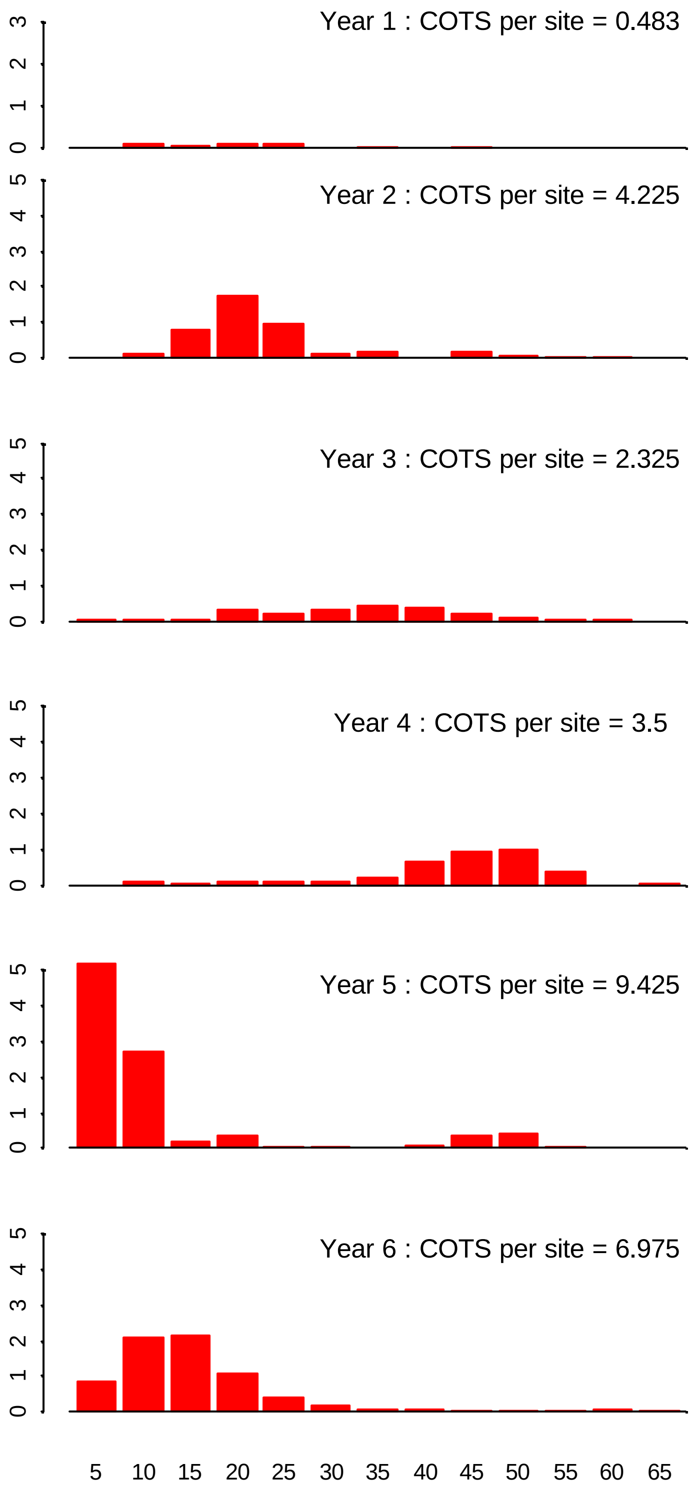

Live Cover
0 10 20 30 40
na
1 2 3 4 5 6
Year

16023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Year 2 : COTS per site = 4.225
Year 3 : COTS per site = 2.325
Year 4 : COTS per site = 3.5
Year 5 : COTS per site = 9.425
Year 6 : COTS per site = 6.975
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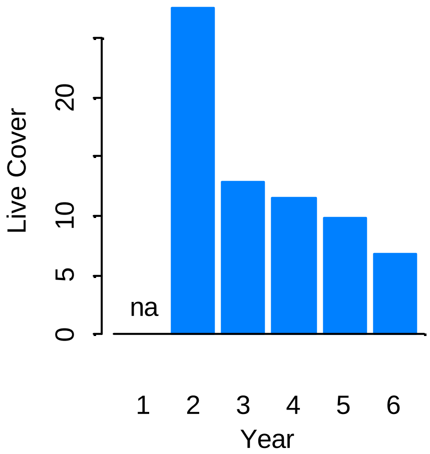
35
40
45
50
55
60
65


Live Cover
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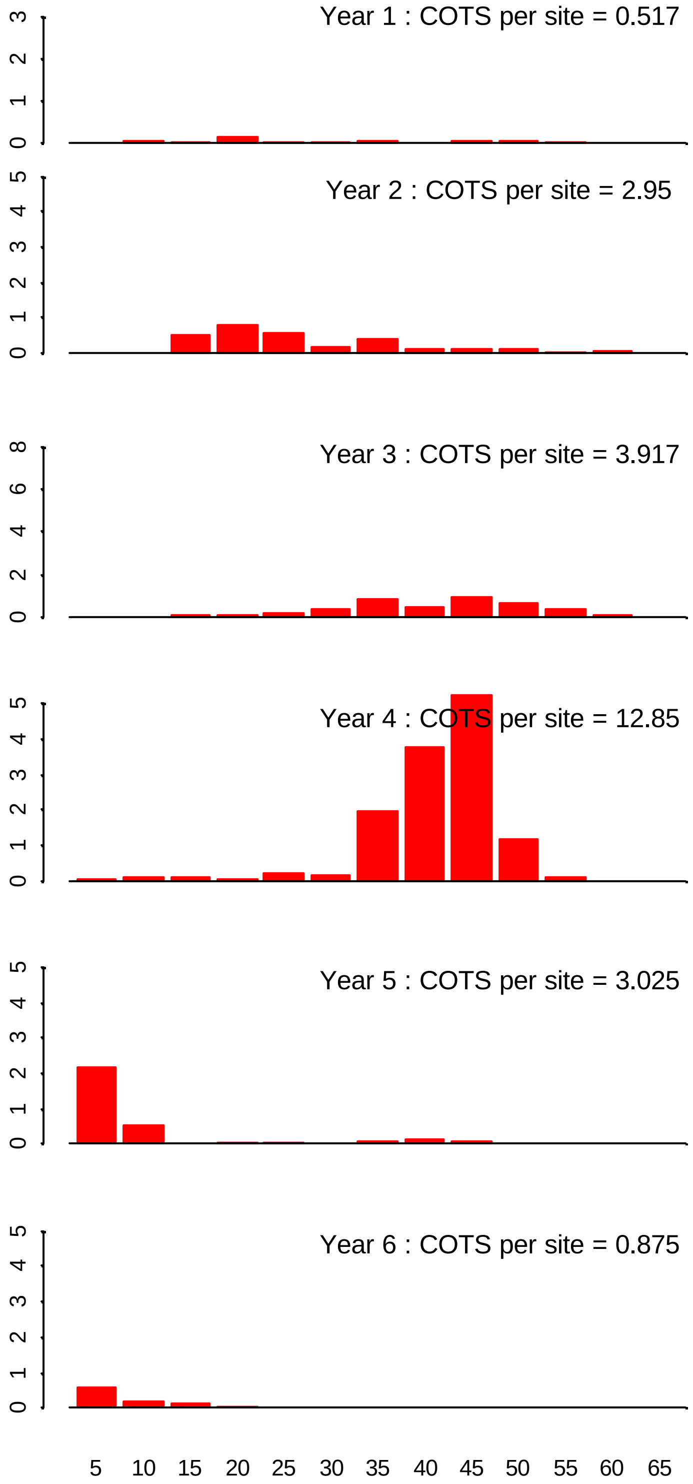
5
6
Year

16024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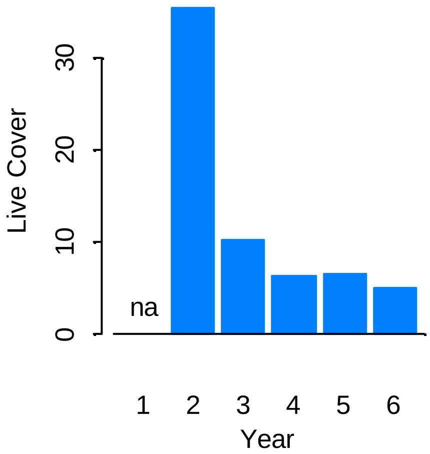
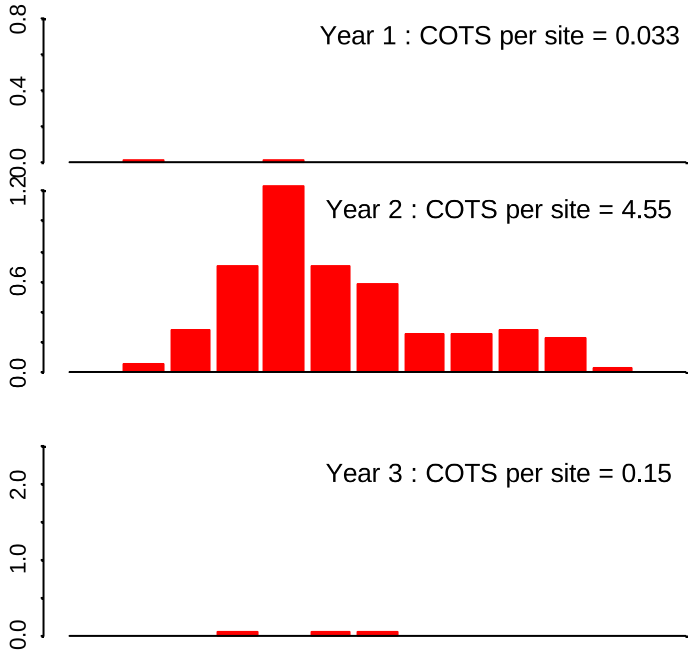
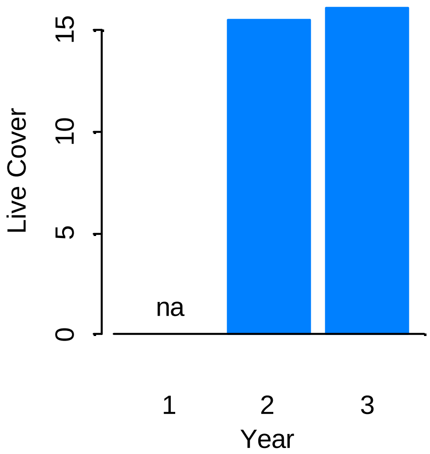
Year 2 : COTS per site = 2.95
Year 3 : COTS per site = 3.917
Year 4 : COTS per site = 12.85
Year 5 : COTS per site = 3.025
Year 6 : COTS per site = 0.875
5 10 15 20 25 30 35 40 45 50 55 60 65

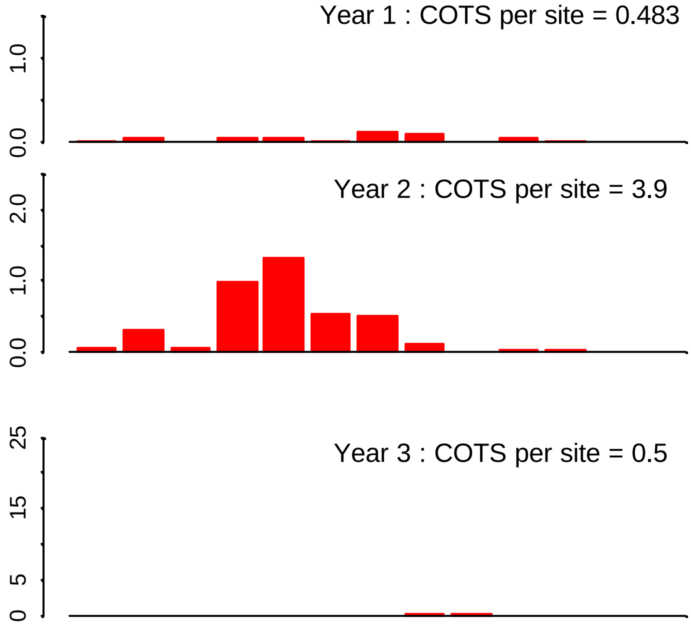

Live Cover
na
1 2 3 4 5 6
Year

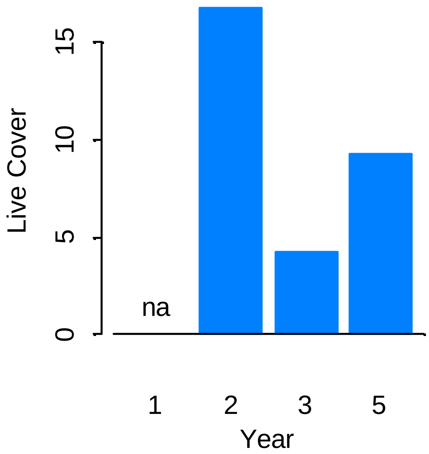
16026

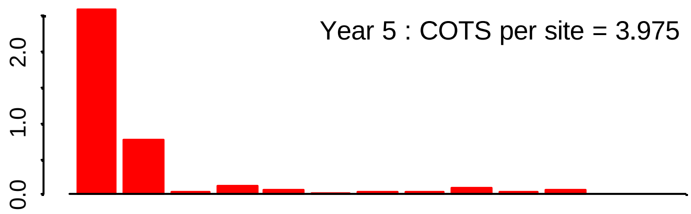

Year 1 : COTS per site = 0.033
Year 2 : COTS per site = 4.55
Year 3 : COTS per site = 0.15
0.0
0.4
0.8
0.0
0.6
1.2
0.0
1.0
2.0


Live Cover
0
5
10
15
na
1
2
3
Year

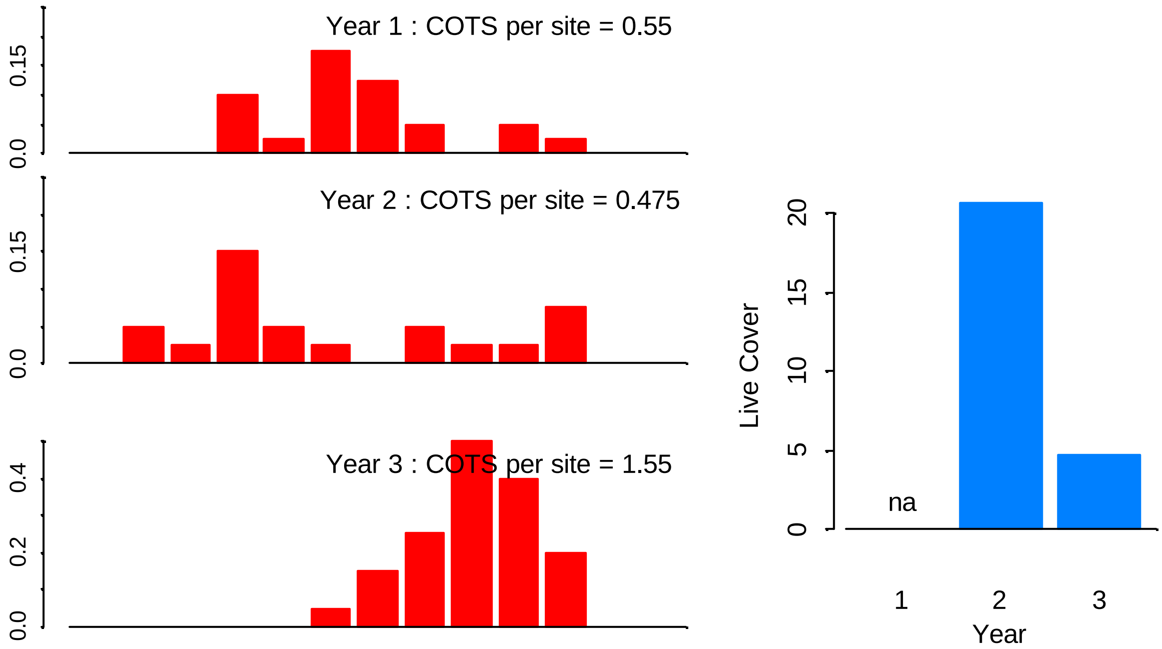
16057


Year 1 : COTS per site = 0.483
0.0
1.0
Year 2 : COTS per site = 3.9
0.0
1.0
2.0
Year 3 : COTS per site = 0.5
0
5
15
25

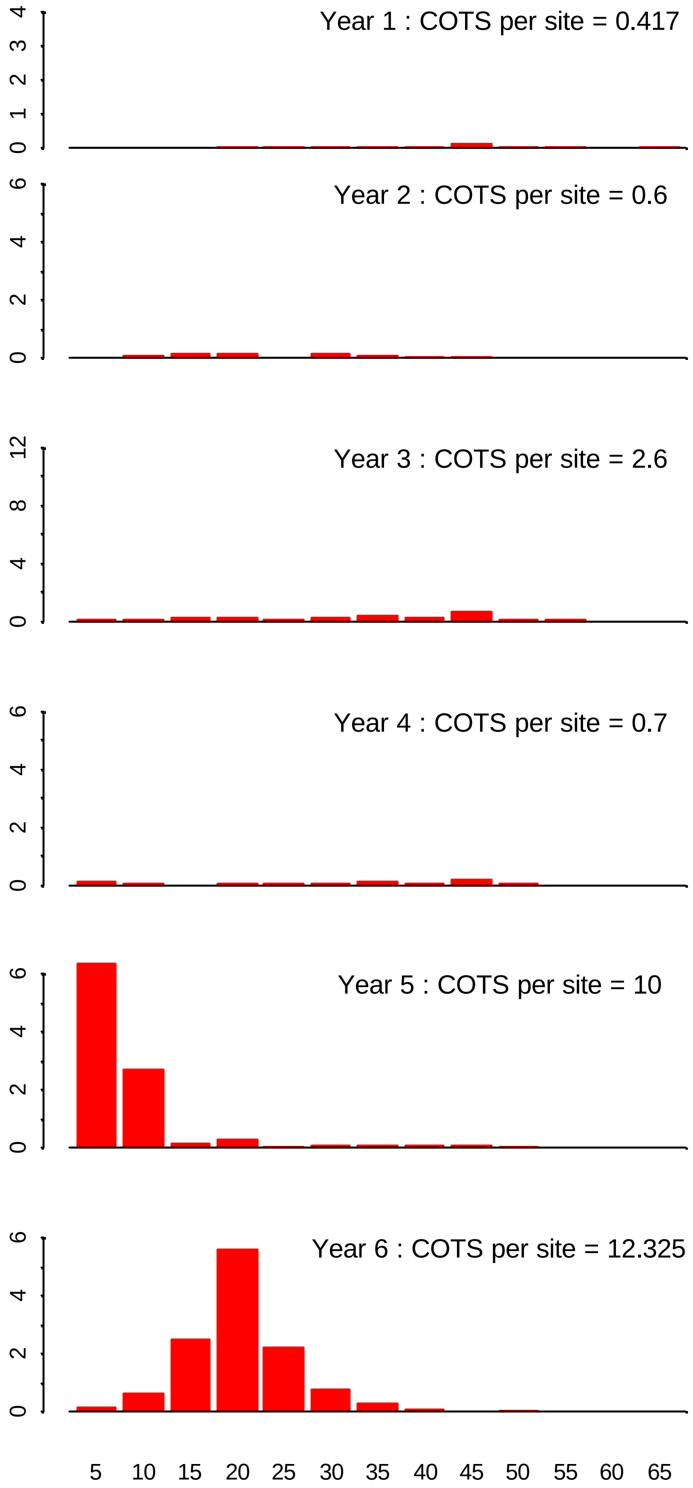

Live Cover
0
5
10
15
na
1
2
3
5
Year

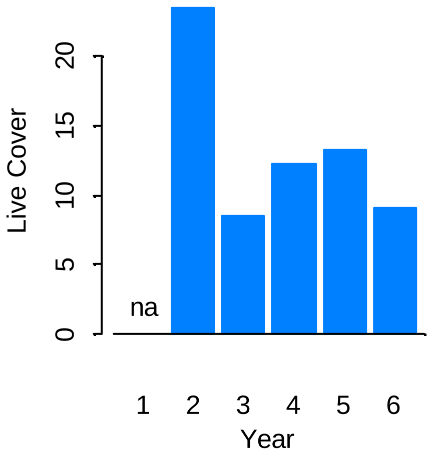

Year 5 : COTS per site = 3.975
0.0
1.0
2.0

16064

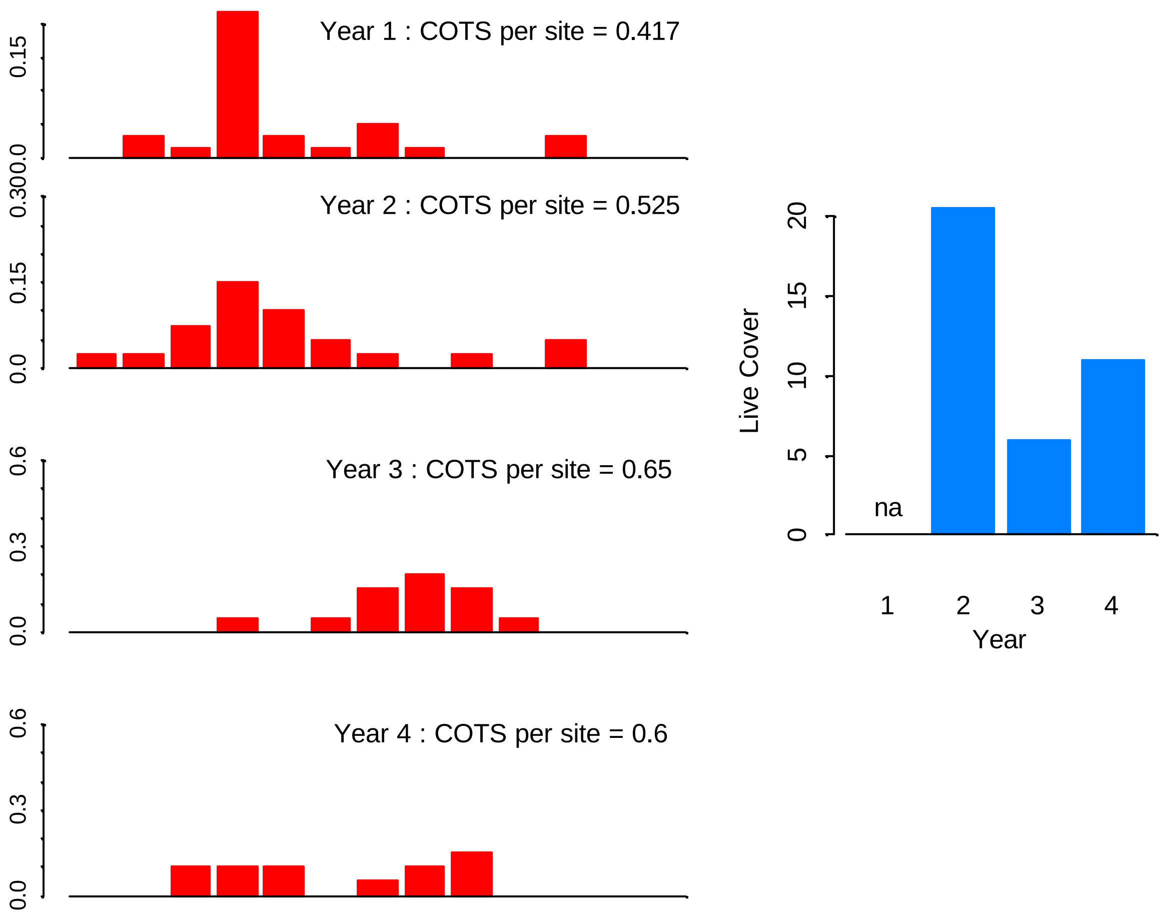

Year 1 : COTS per site = 0.55
0.0
0.15
Year 2 : COTS per site = 0.475
0.0
0.15
Year 3 : COTS per site = 1.55
0.0
0.2
0.4
Live Cover
0
5
10
15
20
na
1
2
3
Year

16068

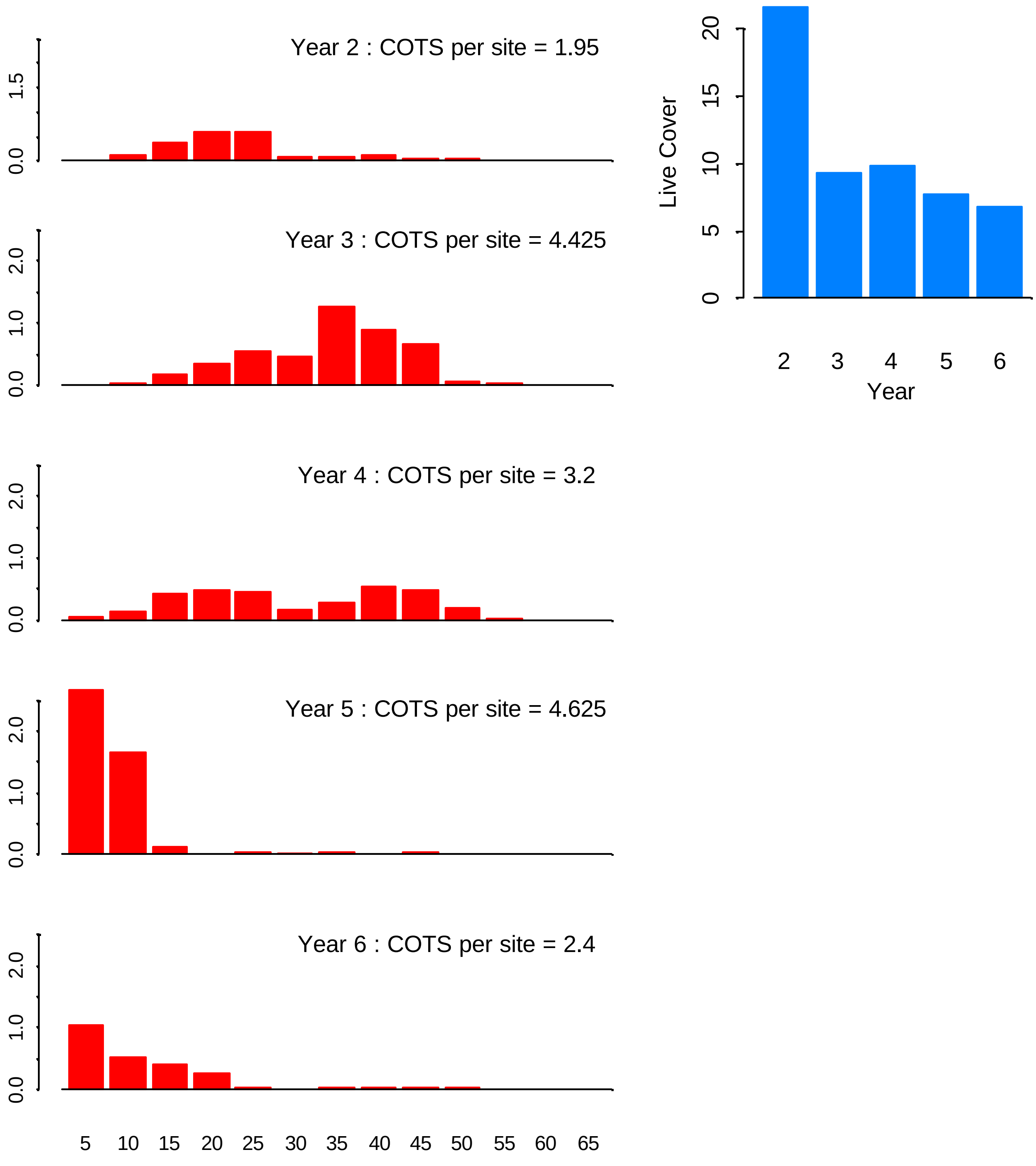

Year 1 : COTS per site = 0.417
Year 2 : COTS per site = 0.6
Year 3 : COTS per site = 2.6
Year 4 : COTS per site = 0.7
Year 5 : COTS per site = 10
Year 6 : COTS per site = 12.325
5 10 15 20 25 30 35 40 45 50 55 60 65


Live Cover
na
1 2 3 4 5 6
Year

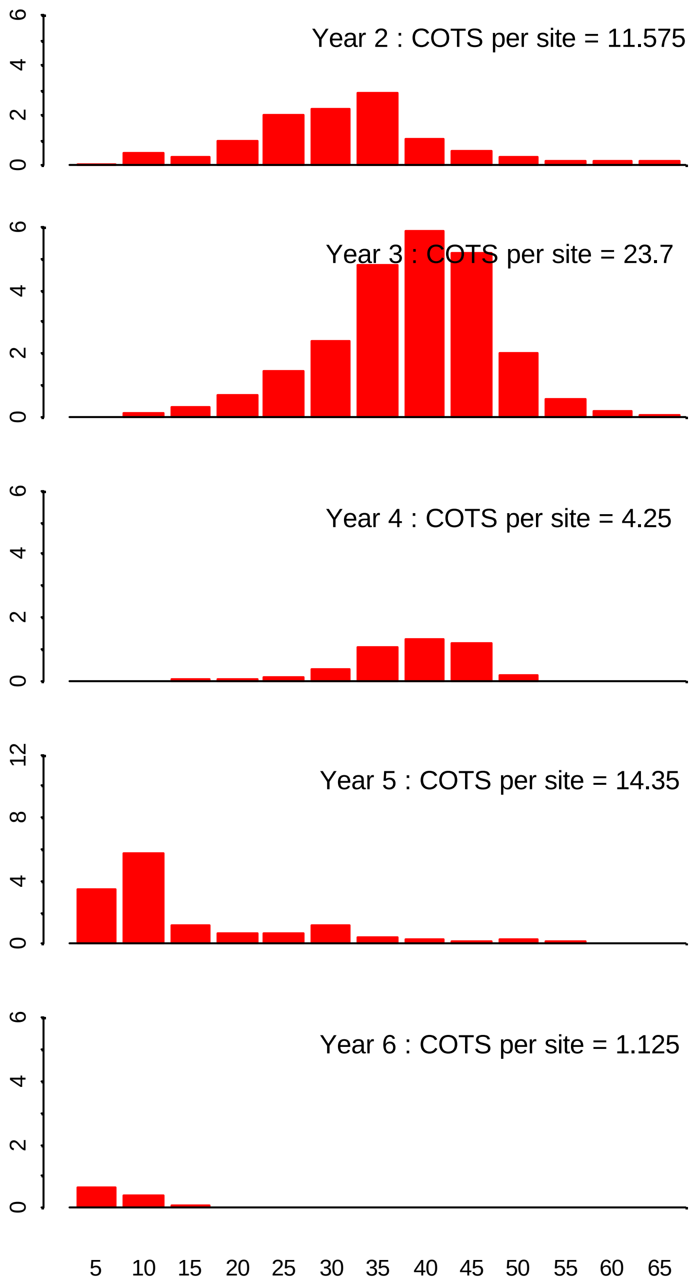
16073

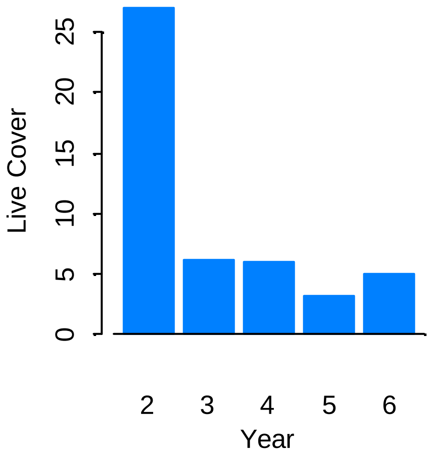

Year 1 : COTS per site = 0.417
0.0
0.15
0.30
Year 2 : COTS per site = 0.525
0.0
0.15
0.30
Year 3 : COTS per site = 0.65
0.0
0.3
0.6
Year 4 : COTS per site = 0.6
0.0
0.3
0.6
Live Cover
0
5
10
15
20
na
1
2
3
4
Year

17004

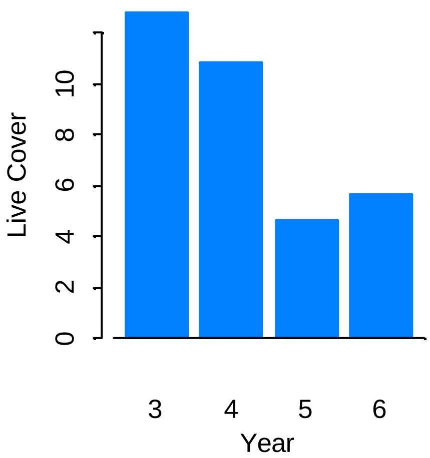

Year 2 : COTS per site = 1.95
Year 3 : COTS per site = 4.425
Year 4 : COTS per site = 3.2
Year 5 : COTS per site = 4.625
Year 6 : COTS per site = 2.4
0.0
1.5
0.0
1.0
2.0
5 10 15 20 25 30 35 40 45 50 55 60 65
Live Cover
0
5
10
15
20
2 3 4 5 6
Year

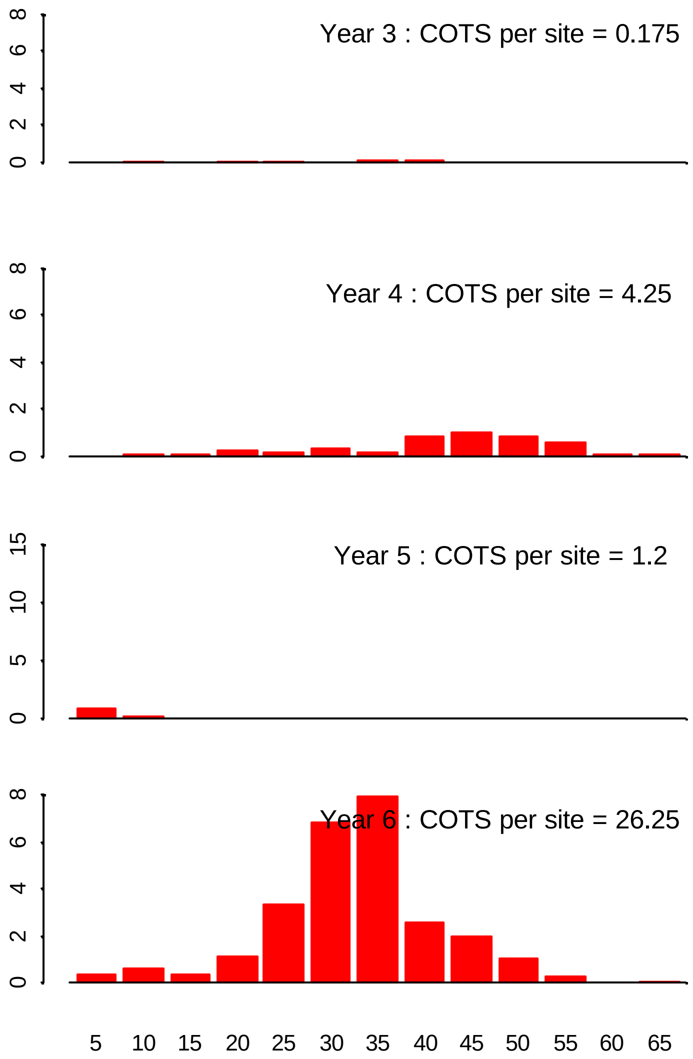
17011


Year 2 : COTS per site = 11.575
Year 3 : COTS per site = 23.7
Year 4 : COTS per site = 4.25
Year 5 : COTS per site = 14.35
Year 6 : COTS per site = 1.125
0
2
4
6
8
12
5
10
15
20
25
30
35
40
45
50
55
60
65

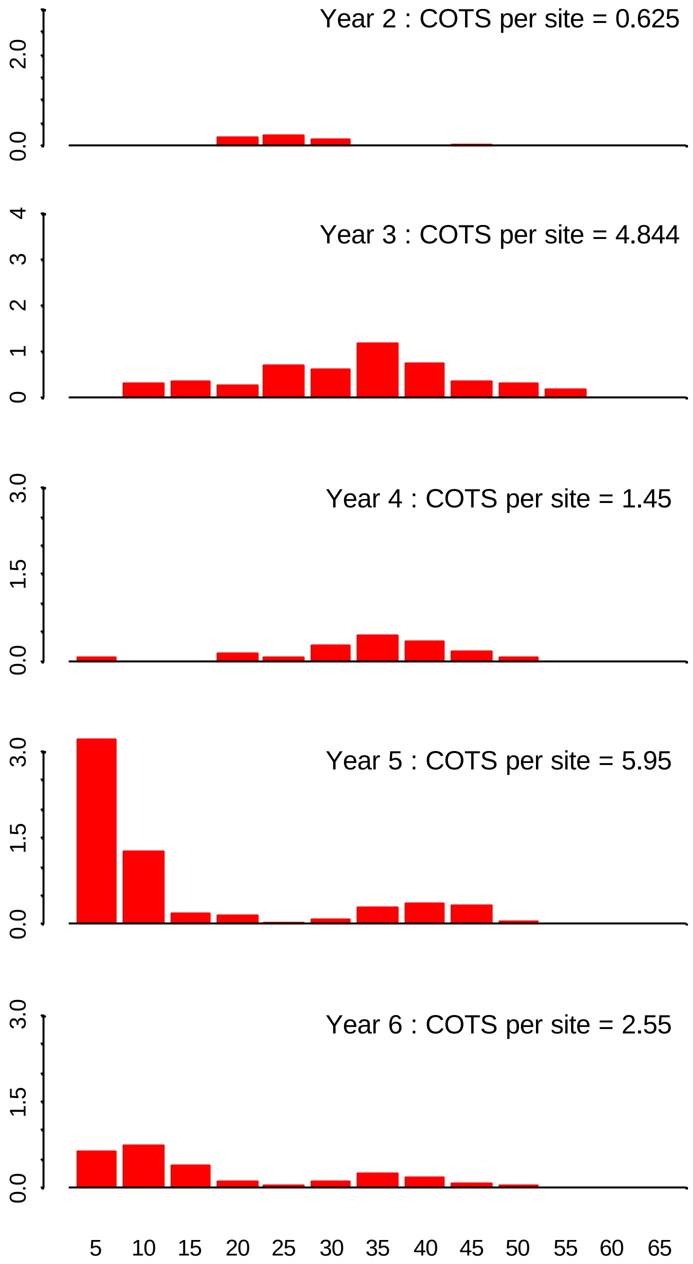

Live Cover
0
5
10
15
20
25
2
3
4
5
6
Year

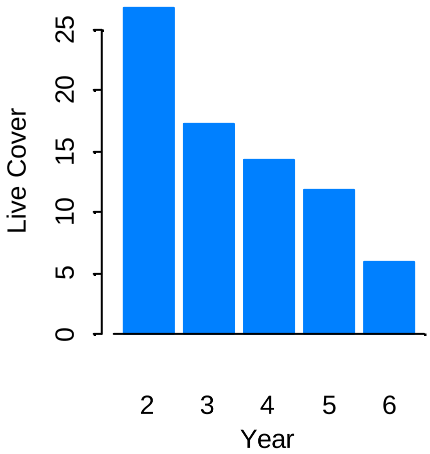
17023


Live Cover
0
2
4
6
8
10
3
4
5
6
Year

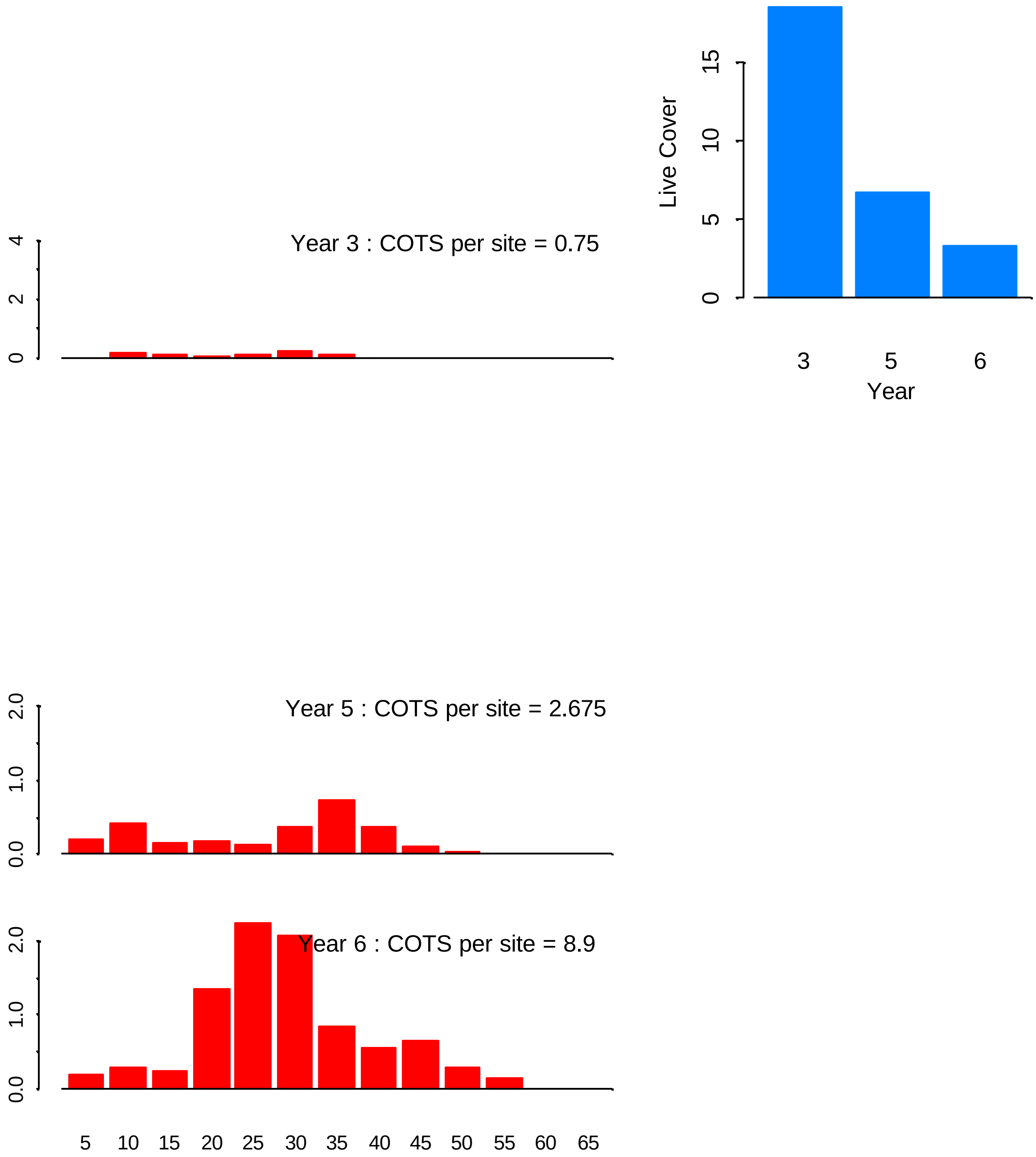

Year 3 : COTS per site = 0.175
Year 4 : COTS per site = 4.25
Year 5 : COTS per site = 1.2
Year 6 : COTS per site = 26.25
0
2
4
6
8
5
10
15
5
10
15
20
25
30
35
40
45
50
55
60
65

17034

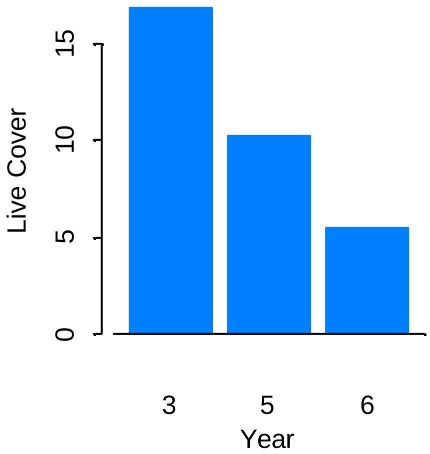

Year 2 : COTS per site = 0.625
Year 3 : COTS per site = 4.844
Year 4 : COTS per site = 1.45
Year 5 : COTS per site = 5.95
Year 6 : COTS per site = 2.55
0.0
2.0
0
1
2
3
4
0.0
1.5
3.0
5
10
15
20
25
30
35
40
45
50
55
60
65

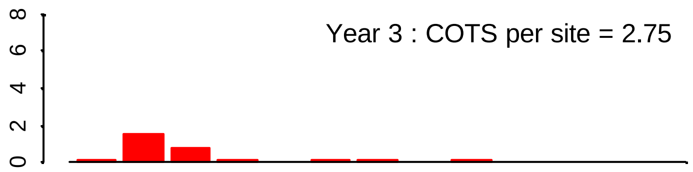

Live Cover
0
5
10
15
20
25
2
3
4
5
6
Year

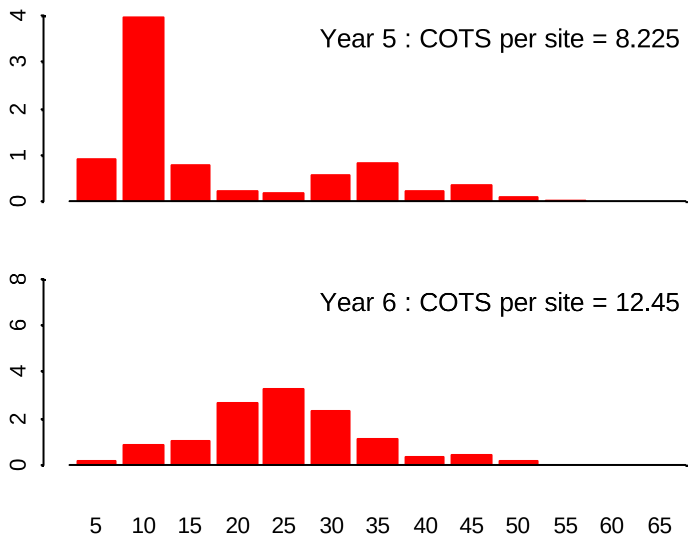
17047


Year 3 : COTS per site = 0.75
0
2
4
Live Cover
0
5
10
15
3
5
6
Year
Year 5 : COTS per site = 2.675
0.0
1.0
2.0
Year 6 : COTS per site = 8.9
0.0
1.0
2.0
5
10
15
20
25
30
35
40
45
50
55
60
65

17064


Live Cover
0
5
10
15
3
5
6
Year


Year 3 : COTS per site = 2.75
0
2
4
6
8


Year 5 : COTS per site = 8.225
0
1
2
3
4
Year 6 : COTS per site = 12.45
0
2
4
6
8
5
10
15
20
25
30
35
40
45
50
55
60
65