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Use of the Traffic Light Method in Fishery Management Planning

Utilisation de la méthode des feux de circulation dans la planification de la gestion de la pêche

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Abstract

The Traffic Light method has been investigated as a framework for stock assessment and fishery management planning in a precautionary approach. The method has been applied in the science advisory process for Northwest Atlantic shrimp stocks and, on a trial basis, for some DFO Scotia-Fundy Region groundfish stocks. It has yet to be applied as a framework for Integrated Fishery Management Planning. This document describes the elements of the method and discusses some of the issues to be considered in its application. It is a progress report and is prepared in support of wider trial applications of the methodology.

Résumé

On a envisagé d'utiliser la méthode des feux de circulation comme guide pour l'évaluation des stocks et la planification de la gestion de la pêche dans une approche de précaution. On l'a appliquée dans le processus de consultation scientifique pour les stocks de crevette de l'Atlantique Nord-Ouest et, à titre expérimental, pour certains stocks de poisson de fond de la région Scotia-Fundy du MPO. Il reste à s'en servir comme guide pour la planification de la gestion intégrée de la pêche. Dans le document, on décrit les éléments de la méthode et discute de certaines des questions à prendre en compte dans son application. Le document est un rapport provisoire, rédigé dans le but d'appuyer des applications expérimentales plus étendues de la méthodologie.

INTRODUCTION

The Regional Advisory Process (RAP) for the Maritimes supports a Fisheries Management Studies Working Group (FMSWG) that promotes research on, and provides a review forum for, general fishery management issues. In 1999, the FMSWG initiated a study of the Traffic Light method as a tool for overall fishery management planning with initial emphasis being placed on its use in stock assessment. This study culminated in a series of three meetings in 2001 that were devoted largely to this topic (RAP, 2001a, b and c). The working group decided that a workbook should be produced to support the practical application of the methodology. The concept adopted was for the workbook to be electronic and subject to revision and addition as the need arises. The present document is an introduction to this workbook that provides a description of the method and guidelines for its application. The main body of the workbook is to be composed of descriptions of fishery system indicators that will serve as the basic building blocks of Traffic Light analyses. The first of these indicator descriptions were accepted by the FMSWG at its May 2001 meeting and are appended to the proceedings of that meeting (RAP, 2001b). The most recent version of the present document, along with up to date indicator descriptions, is available on the Maritimes Region Intranet site under the Marine Fish Division's Virtual Data Centre. This site should be consulted for current information on methodology and applications.

The guidance the present document provides reflects the opinions of the authors. It does, of course, draw heavily on the ideas that many colleagues expressed in meetings of FMSWG and in stock assessment meetings where the method was given pilot applications. Nonetheless, as might be expected at this initial stage of development, there are many aspects of the methodology on which there is no consensus. Also, there is no experience yet in application of the method to an entire fishery management planning process. Thus, this introduction is almost exclusively about the application of the Traffic Light method to stock assessment. However, most aspects of the methods discussed should be of fairly general applicability.

A glossary is provided (Annex 1) as this is a new method and to some extent it has been necessary to develop a vocabulary to describe it.

Definition of the Traffic Light Method

The terminology "Traffic Light approach" was coined by Caddy (1998, 1999) to describe a type of precautionary management framework suitable for use in fishery assessment in data-poor situations. He proposed a system of red, yellow and green lights to categorize multiple indicators of the state of a fishery and ecosystem in relation to defined Limit Reference Points. Integral to the approach was a set of Decision Rules on management actions to be taken depending on the numbers of lights of each colour that were recorded, measures becoming more restrictive as the proportion of reds increased. This defines the Traffic Light approach as a precautionary management framework that:

- uses a multiplicity of indicators of system status,
- classifies the current state of indicators in relation to Limit Reference Points using a system of green, yellow and red lights, and

- establishes management response rules associated with some integrative function of light colours.

The term "Traffic Light approach" is replaced in this document by "Traffic Light method" to distinguish it as a methodology rather than a general philosophy such as the Precautionary Approach and the Ecosystem Approach.

Definition of the Precautionary Approach

The Food and Agriculture Organization of the United Nations (FAO) is the lead agency in promotion of the precautionary approach to fisheries. The poor performance of fisheries management on a worldwide basis led to a call for new concepts that would result in a more responsible approach to fishing. A Code of Conduct for Responsible Fisheries was introduced by FAO in 1995 (FAO, 1995) to establish (voluntary) principles and standards for the conservation, management and development of all fisheries. The Code promotes the precautionary approach and explains some of its implications. The agreement resulting from the United Nations Conference on Straddling Stocks and Highly Migratory Fish Stocks (UN, 1995) is the first to imbed the concept of the precautionary approach in a legally binding treaty. An annex to this agreement provides guidelines for its application.

Canada's 1997 Oceans Act legislation requires promotion of "the wide application of the precautionary approach to the conservation, management and exploitation of marine resources in order to protect these resources and preserve the marine environment". The discussion paper produced by FMSWG on regional application of the precautionary approach (RAP, 2000) defines a management system that embodies the precautionary approach as one in which:

- objectives are set,
- plans to achieve them are implemented (strategies),
- unacceptable outcomes are defined (Limit Reference Points),
- uncertainty is taken into account,
- system performance is monitored (indicators), and
- there is pre-agreement on the corrective actions to be taken if limits are approached (Decision Rules).

In applying these principles to fisheries, the ecosystem effects of fishing and socio-economic conditions in the fishery are to be taken into account. This definition is receiving widespread recognition as an appropriate set of criteria for measuring the consistency of fishing plans with the precautionary approach.

There are two conservation considerations relevant to the regulation of fishing embodied in the precautionary approach as expressed in the UN Fisheries Agreement and other documents. The first is that fishing should be restricted to moderate levels to avoid the possibility that resource productivity or ecosystem functioning is deleteriously affected directly as the result of fishing. The second is that, when a natural phenomenon adversely affects stock productivity, fishing activity should be curtailed or, if necessary, eliminated so as not to exacerbate the situation. Thus, indicators that illustrate the present state of the resources in relation to historical states are not the only ones required.

Indicators that give early signals of a change in stock dynamics and in factors that are known or hypothesized to affect stock dynamics are necessary also.

The Management Context

An integrated fisheries management planning (IFMP) system was introduced by DFO in 1995. The most recent description of the process is provided in a draft DFO internal document entitled "Framework and Guidelines for Implementing the Co-Management Approach Volume II: Integrated Fisheries Management Plans" dated January 1999. An IFMP provides a description of the fishery and of current stock status, fishery objectives, strategies and implementation plans, and an annual performance review process. A 'fishery' may be defined on the basis of a single stock, a single species or at a multi-species level. Development of multi-year plans is preferred to encourage a longer-term perspective in planning. Various degrees of success have been met in developing such plans.

A new initiative was taken by DFO in 2000 to introduce Objective-Based Fisheries Management as an enhancement of the IFMP process. The primary thrusts of this are:

- clear and achievable objectives that are quantifiable and thus measurable,
- compatibility of conservation, social and economic objectives,
- introduction of risk analysis as a framework for a precautionary approach, and
- enhanced post-season analysis based on system performance monitoring.

Pilot applications of these enhanced IFMP guidelines are scheduled to begin in 2002.

A new policy framework is under development for Atlantic fisheries. This will provide a much needed underpinning for management planning as it is almost 20 years since the last comprehensive policy review (Kirby, 1982). Although the new policy is not yet finalized, the discussion paper now available (DFO, 2001) allows the major thrusts of the policy to be anticipated. Three objectives are proposed; conservation, orderly harvesting and shared stewardship. There is clearly an intention that the industry itself, in time, will have the authority and responsibility over management of the fisheries within broad constraints set by government.

Why Use Caddy's Traffic Light Method to Apply the Precautionary Approach?

The commitment by DFO to take a precautionary approach to the management of fisheries and of ocean uses in general requires changes to the form of scientific advice and to the way fisheries have been managed. The Traffic Light methodology provides a single framework within which these needs can be addressed. Use of the method is not in itself precautionary. However, if the assignments of lights to indicators are based on definitions of unacceptable outcomes, i.e. on limit reference points, and the results are linked to a set of appropriate decision rules, its usage meets precautionary approach criteria. The emphasis on having a comprehensive set of indicators of system performance is a commonality between the Traffic Light and precautionary approaches. Information on the disparate elements of a plan can be arrayed in a common format in support of rational decision-making. Gaps in information on some plan elements will be clearly evident, encouraging remedial action.

The Traffic Light method can be used to assess the status of all stocks whether rich or poor in data. The great majority of stocks fall into the data-poor category and scientific advice for them has often been qualitative or semi-quantitative and subjective. Application of the method to these stocks requires that the advice is formulated in a rigorous manner that gives explicit weights to all of the available information and this should be an improvement over the subjective evaluations of the past.

The methodology can improve advice also for data-rich stocks, i.e. those for which sequential population analysis (SPA) is possible. It focuses scientific attention on the biology of the resource and its interactions with the environment and the rest of the ecosystem, i.e. on developing an understanding of the factors affecting productivity. These insights will provide a broader and sounder basis for policy development than the SPA method, which, as used in the past, simply provides an accounting of population changes.

The method provides a way that fishermen's information can be readily incorporated directly into analyses of stock status and of other elements of the plan. Fishermen's experiences, e.g. collected through structured interviews, could thus become an integral part of stock assessment and plan evaluation, possibly answering the longstanding criticism that fishermen's knowledge is not utilized. This is a key element to the success of any co-management initiative.

The methodology allows results to be described simply and this, combined with the visual impact of traffic lights, promotes understanding of results. This should help in securing buy-in by the industry to the associated decision rules, an essential element of successful management.

Why not use the NAFO/ICES Precautionary Frameworks?

The Traffic Light method is not the only management framework that could be used to implement a precautionary approach. Guidelines in the UN Fisheries Agreement (UN, 1995) use the Maximum Sustainable Yield (MSY) concept as the foundation of limit reference points for stock conservation. ICES and the NAFO Scientific Council have conformed closely to the specifics of the UN guidelines in proposing precautionary frameworks using complex mathematical models for derivation of reference points in relation to MSY.

This methodology is an extension of the principal stock assessment methods that have supported fishery management for over 50 years. As a result, its limitations are well known. The principal ones are:

- it is possible to apply it only to fisheries on stocks for which there is a lot of data,
- MSY-based models require an assumption about the relationship of recruitment with spawning stock size but there is no scientific consensus on the nature of this relationship,

- these are single-species models that assume that future environmental and ecological conditions will mirror the past,
- decision rules are dependent on only the two attributes, biomass (B) and fishing mortality (F) and it is questionable in many circumstances if the SPA/catch projection method used for monitoring and feedback provides sufficiently accurate information to support the rules,
- the frameworks relate only to decision making at the scientific/political interface and not to the entire fishery system.

Elements of this framework could be included as indicators in a broader Traffic Light framework, if considered worthwhile, but this should be decided upon on a case by case basis.

DESCRIPTION OF THE METHOD

Caddy (1999) illustrated the Traffic Light method in a single figure showing, on the left side, a column of lights giving the status of the most recent data point for each indicator in relation to its limit reference point and, on the right, a key providing decision rules based on the number of lights that were red (Fig. 1). This proposal is elegant in its simplicity. It has three elements – a reference point system for categorization of indicators, an integration algorithm and a decision rule structure based on the integrated score. Koeller et al. (2000) introduced the idea of using a 'retrospective' table of lights to communicate historical trends in shrimp stocks (Fig. 2). This adds information on recent trends in indicators that could help in decision-making. However, integration of such a time-series of scores to form a longer-term historical index of stock status, as introduced in applications for some groundfish stocks (Fig. 3), raises new issues (RAP 2001a). In particular, data series of different lengths may bias trends in the Traffic Light indices. It is necessary to distinguish between a **Traffic Light Precautionary Management Framework**, as proposed by Caddy, and a **Traffic Light Stock Status Index**. Caddy (in press) strongly emphasizes that the former is the key element of the method. Uses are foreseen for an historical index also, however. These can provide a basis for multi-stock integrations that will be useful in management frameworks for regulating ecosystem use. Furthermore, historical tabulations of indicator states alone provide concise summaries of stock assessment inputs that are readily understood by non-scientists.

Definitions of Terms

Elements of the fishery can be conceptualized as having attributes. Attributes of fish stocks include their biomass, growth rate, and the mortality on them due to fishing. Fishery attributes include accuracy of landings statistics, frequency of discarding, and observance of mesh regulations. Socio-economic attributes include revenues, employment, earnings, and their distributional characteristics.

A specific method of estimating an attribute is called an indicator. As an example, the population attribute 'biomass' can be estimated with indicators such as a research vessel survey estimate of mean weight per tow or an estimate of total biomass from an SPA.

Sometimes indicators have been called 'performance measures', but these terms are not synonymous. Performance measures refer specifically to 'control' indicators that measure organizational success in program delivery. Only a subset of the indicators that define resource and ecosystem status is directly influenced by managerial intervention. Others, such as those measuring growth or environmental conditions, are 'state' indicators. It is recommended, therefore, that the term 'indicator' be used as the generic descriptor of data time series.

Management plans must define strategies for meeting plan objectives. The precautionary approach prescribes the use of reference points to define strategies. Reference points are values of indicators defined on some technical basis, which can be used as guides for fishery management, e.g. specific values of fishing mortality, fishermen's income or frequency of discarding.

Decision rules, except in the simplest cases, will be based on some integrated score of indicator values. An overall summary of indicators may prove useful for some applications but, for groundfish stock status assessment, summarization to an intermediate 'system characteristic' level has been considered preferable. Characteristics are descriptors of the factors defining the productive capacity of a stock, such as abundance, production, fishing mortality and environment.

Descriptions of Indicators

While almost any product from a relevant data source may be proposed as an indicator of an attribute of interest, these 'candidate indicators' need validation before reliance can be put on them. In the case of stock status, for example, indicators of F and B are well understood and are interpretable in terms of stock status directly. Others, such as those for growth and condition factor, are less directly linked to stock status. For these, interpretation is linked to the status of other attributes, such as environmental conditions, and possibly B. There are also indicators, such as those for stock and fishery distributional characteristics, the meaning of which is presently more difficult to interpret. These last provide examples of the need to extend our understanding of the biology of fish populations. Indicator validation may be based on biological knowledge, theoretical considerations or, at least initially, by analogy with similar indicators for other stocks/plans that already have an established scientific basis. The most suitable indicators are those which are easily and precisely measurable, clearly interpretable and sensitive to change in the status of the attribute.

Indicator descriptions are the basic building blocks for application of the Traffic Light method. Annex 2 provides a template for a description of an indicator. This description gives the theoretical and practical evidence for the relationship of indicators to the status of an attribute, the results of research on its responsiveness to change in this attribute and recommendations on the most appropriate ways of calculating indices and reference points. It is necessary that there be some consensus among analysts on applicability and reliability of indicators. Thus, indicator descriptions need to be subjected to an acceptance process based on peer review of analyses and documentation of consensus opinion. The basic standards for description of indicators need to be met at the time of introduction of new indicators.

Stock Assessment Indicators

Only information that casts light on some element of the status of a stock should be included among the indicators used in assessment of its status. Relevant information includes fishing mortality, biomass, recruitment, fish condition, growth rate, size/age at maturity, and distributional characteristics. Indicators of environmental (oceanographic) change would be relevant also, but only if there is evidence that these relate directly to the productivity of the stock.

There are several types of indicators that are not appropriate to include directly in the assessment of the status of a stock, because they are fishery, not stock, status indicators. These are:

- indicators of ecosystem effects of fishing for a stock, e.g. mortalities of bycatch species or seabed disturbance,
- regulatory non-compliance, such as under- or non-reporting of catches, dumping/high-grading, discarding of undersized fish and misreporting of area of capture, and
- indicators of performance of the management plan with regard to its economic, social or other objectives.

However, any of these other types of indicators may enter into decision rules, as qualifiers to stock status information, affecting the choice of regulatory actions. Also, information on non-compliance could be used as qualifiers on the reliability of some of the indices of stock status.

Indicators of Ecosystem Effects of Fishing

Direct effects of fishing on ecosystems include the size-selective removal of target species and incidental mortalities of non-target fish species, marine birds, turtles and mammals taken as bycatch. High levels of fishing could extirpate particularly vulnerable species from an area, reducing local biodiversity. Bottom fishing results in some disturbance of the seabed that in some cases, such as dredging and trawling, can result in substantial incidental mortalities of benthic fauna. Indirectly, the selective removal of commercially desirable species in large quantities by fishing has some effect on trophic level balance (predator/prey relationships), and could possibly have a deleterious affect on the productivity of trophically dependent species.

Institutional structures to deal with 'oceans' level management issues are in their infancy but it is clear that, within the fisheries sector, the application of measures to meet ecosystem goals will occur at the planning level of individual fisheries (Coffen-Smout et al., 2001). Already, there are various provisions for the protection of 'sensitive' species, e.g. marine mammals. Indicators of performance of these measures need to be developed and included in plans.

Indicators of Economic and Social Outcomes

In applying precautionary approach principles, socio-economic conditions in the fishery are to be taken into account. This is, in any case, a necessity if a management plan is to work effectively in meeting industry goals. Ensuring satisfactory returns from fishing is also a precondition for effective implementation of restrictions because getting agreement on reductions in catches is difficult or impossible when fishermen are already struggling for economic survival.

Economic/social indicators are relevant at the fishery, not the stock, level at least in multi-stock fisheries. Even then, there are interactions between fisheries due to multiple licensing, e.g. groundfish – lobster, and it may only be meaningful to track these indicators at the fleet level. What is useful for indicators will vary among fisheries and it is preferable for indicators to be developed in the context of establishing quantifiable objectives during planning.

Ideally, indicators could include amount of revenue, number of licences, number of crew, earnings per crew, earnings versus those in other industries, revenue concentration, fish prices and cost/earnings of enterprises. Historical studies by both DFO and outside sources could provide useful benchmarks.

Indicators of Regulatory Compliance

A high level of compliance with regulations is essential to the success of any plan but development of compliance indicators is at a rudimentary level. In the past, the indicators available for planning have been predominantly surveillance indicators, e.g. number of at-sea boardings or hours of overflights. Compliance indicators would provide estimates of the frequency with which particular regulations were being violated and ideally would provide a quantification of the effects of these violations, e.g. the tonnage of fish involved. Of particular importance are the completeness of landings statistics and the extent of discarding at sea. Innovative methods are required to obtain this information as it cannot be obtained from traditional surveillance methods. Controlled observations at sea by fishery observers in accordance with an experimental design offer possibilities (e.g. Allard and Chouinard, 1997), as do comparisons within and among existing data bases to detect inconsistencies. Surveys of fishermen on compliance levels has met some level of success elsewhere (e.g. Sutinen et al., 1990). Whatever methods are adopted, monitoring should be adequate to provide reasonable confidence that causes of plan failures can be accurately diagnosed.

Determination of Reference Points

The Traffic Light method, as originally conceived, requires that the state of each indicator be categorized in relation to the colours green, yellow and red. There is no necessity for the method to be based only on three colours or, indeed, on colours at all (numbers would suffice equally well). However, for purposes of this section on determination of reference points, a three-colour system is assumed.

The many technical reference points that have been proposed for guidance in the management of fishery resources can be placed in two categories, those defining limit values and those defining target values of indicators (Caddy and Mahon, 1995). A limit reference point is associated with an unacceptable outcome in a precautionary approach context. A target reference point, in contrast, defines a condition that it is considered desirable to achieve. For example, $F_{0.1}$ has long served as a benchmark for management for Atlantic finfish stocks. It is a target reference point that has been viewed as providing an optimal balance between conservation and economic benefits.

To tie Traffic Light outputs to the requirement of the precautionary approach for definition of limit reference points, the yellow/red boundary should equate to a limit reference point. The green/yellow boundary could be used to define a buffer zone between fully satisfactory conditions (green) and those that give warning of proximity to unacceptable conditions (yellow). This would be analogous to the buffer zone proposed in ICES/NAFO applications of the precautionary approach.

It is not appropriate to call the green/yellow boundary a 'target'. The establishment of targets is appropriate only for indicators that are influenced by management actions (control indicators), e.g. fishing mortality or fishermen's incomes, and not for indicators such as water temperature or recruitment (state indicators). Thus, universal application of the term 'target' at the indicator level is not meaningful. Targets could be incorporated in decision rules (see below). However, targets are related to optimization of benefits from the fishery and are not an element of the precautionary approach (although there has been a suggestion that they may be of supplementary value in achieving effective precautionary approach implementation, e.g. Caddy, in press).

A number of options are available for establishing boundaries that equate to precautionary reference points for a Traffic Light indicator. Arbitrary boundaries can be set based on the simple conceptual model that extreme deviations from previous values of an indicator, if on the 'undesirable' side, are viewed as warning signals, even if the full significance of these values is not understood. Two such methods (among many alternatives) have been favoured in initial applications to groundfish. The primary option has been to establish the limit reference point (the yellow/red boundary) based on a percentage (e.g. 60% or, inversely, 167%) of the average value, when there is a long time series of data. The average value of the indicator in this case serves as the yellow/green boundary. In cases where this is not appropriate, i.e. where the possible range of the data is restricted, setting boundaries at the 33rd and 66th percentiles has been favoured. In both of these cases, the yellow/green boundary, by dividing the data into two groups, provides for a more detailed scaling of results. In the first case, the yellow zone so created could be considered as a broad buffer zone but, in the percentile case, this is a less tenable proposal.

The above approach has the advantage of simplicity but it is not immediately obvious that a common rule applied to several indicators automatically scales them 'appropriately'. It is preferable to have an exogenous way to identify limits that reflect the biology of the resource. There are, as yet, no cases examined where a reference point could be set based directly on experimental evidence. Although recent research suggests that it may be possible to establish reference points for fish condition from the results of laboratory experiments (Dutil and Lambert, 2000) more work is required even in this case. In the absence of an objective basis for indicators, the preferred method is for boundaries to be established subjectively based on expert scientific judgement. Where a great deal of scientific expertise is available, as is typically the case in stock assessment committees, relying on the judgement of researchers and other knowledgeable individuals is a widely accepted practice. A Delphi, or some other structured decision-making approach, could be used as an aid to decision-making. For groundfish, long time series of data are available that allow identification of indicator states during historical periods when the stock status overall was considered to be 'good' and 'bad'. Our experience is that, when there is such an agreed historical perspective, boundaries are not difficult to agree on. Alternatives include the use of theoretical calculations. The target fishing mortality $F_{0.1}$ provides an example of using a theoretical calculation. The yield per recruit theory on which it is based has a long history of usage and its limitations are well understood. It provides an objective basis for definition of a 'moderate' level of fishing in relation to the assumed growth and natural mortality characteristics of a stock. (It is, nonetheless, an arbitrary choice supported by a strong scientific consensus.) For others see Caddy (1999).

Setting boundaries for short time series is particularly problematic, as the data are unlikely to span the full dynamic range of an attribute. When there is a long time series available that also provides data on the attribute in question, the two series can be inter-calibrated and the boundaries for the long series applied to the short one. Otherwise, the only option is to resort to expert opinion. It is not appropriate to apply statistical rules, such as basing boundaries on the mean and 60% of it, in such cases.

Integration of Indicators

Some form of integration of indicator values is required in support of the decision making process. Integration has two aspects, scaling the indicators to make them comparable and applying an operation to summarize the results from many indicators. Caddy (1998, 1999) presented the simplest case where indicators were scaled by converting their values to traffic lights, and decisions were made based on the proportion of the indicators that were red. (Although Caddy illustrates three traffic lights (Fig. 1), his decision rule requires only two – green and red.) In many applications there will be sufficient data to support more complex decision rules. This section addresses the main issues that have been identified so far in more complex applications. These are: what level of integration is appropriate for utilization of indicators in decision rules; on what bases, if any, should indicators be weighted in integration; and how can the integration be performed to minimize the loss of information? Four methods of integration are compared. One of these, the Fuzzy Set method, is described in detail as it performs well in retaining information during integration and provides also an established mathematical methodology for constructing decision rules. Fuzzy Sets and Fuzzy Logic are not yet in wide use in fisheries although there are some cases (Mackinson and Newlands, 1998; Mackinson et al., 1999; Saila, 1997).

Characteristics

In Caddy's Traffic Light example (Fig. 1), his decision rule is based on an overall summarization of indicators (the number of red lights). This may well be the only option available when there are very few indicators, but more complex decision rules can be supported for many stocks. The FMSWG (RAP, 2001a) identified the main questions to be addressed during an assessment as:

- What is the size of the resource?
- How fast is it renewing?
- How are human actions affecting the stock?
- How might these things change (due to environment, ecological regime shifts, and intrinsic variability e.g. in recruitment)?

and considered that these should be answered separately when data are available to do so.

These questions can be translated into system 'characteristics' of the productive capacity of a fish stock. A characteristic is defined as a conceptual entity based on a number of indicators, the purpose of which is to aggregate similar indictors for further analysis or discussion. Productive capacity is itself defined as the total losses, in biomass, a stock can withstand from all anthropogenic sources while still maintaining itself.

The following descriptions of characteristics are proposed:

- **Abundance** – describes the size of the population providing the production. The historical dependence on abundance (biomass) to describe stock status has assumed (implicitly or explicitly) that any given biomass can and will produce with a constant production to biomass ratio.
- **Production** – includes effects of growth, survival and recruitment. This is the most direct measure of productive capacity if appropriate consideration is given to non-anthropogenic demands.
- **Fishing Mortality** – provides a direct description of the impacts of fishing. A more complete description should include other sources of anthropogenic mortality (habitat, unrecorded fishing effects, etc.).
- **Ecosystem/Environment** – may be treated as one or two characteristics. Each describes the external factors affecting the stock, most of the distinction being whether they are biological (ecosystem) or physico-chemical (environment). Each may also reflect some aspects of anthropogenic effects.

Weighting

The use of multiple indicators raises the problem of how much weight each should be given. Indicators could be weighted in relation to:

- their degree of independence when derived from the same data,
- the availability of multiple indicators for the same attribute,
- the relevance of the attribute,
- the extent to which the indicator provides a true measure of the attribute, and
- the precision of the indicator estimate.

Data series should not be down-weighted simply because they are of shorter duration than other indicators. These short indicator series may be highly relevant to the issue of stock status, such as those derived from joint DFO-Industry surveys. There is likely to be a higher uncertainty about where boundaries should be set for a short indicator, because the full dynamic range of the indicator is not known, and it is in this process that the shortness of data series should be recognized. Weighting, if any, should be dependent on the same criteria as for other indicators.

The degree of independence of indicators is the factor that has generated the most discussion about weighting. An indicator may, at least in part, be a derivative of another indicator (correlated indicators). For example, SPA provides estimates of F, B and recruitment that are to some extent dependent on the data series used for model calibration. Can SPA output be considered as providing indicators independent from those provided by the surveys that are used as input? It can be argued that there is an advantage of having redundant information, as the raw index could show different trends or variability in more recent years. On the other hand, if output from a model such as SPA is acceptable, e.g. no retrospective pattern and relatively good precision, there are arguments for it alone to be used. It is clear, however, that, if problems with the SPA are impossible to resolve, it is preferable to use the original data series as the indicator. A concern about not using an SPA when one is available is that cohort information in the data is being lost. Cohort effects are not easy to obtain from other Traffic Light indicators. In the end, however, the purpose is to obtain the best aggregate of the available information and what constitutes this has to be judged on a case by case basis.

Weighting issues arise even when indicators of an attribute are independent, e.g. derived from separate sources. For example, integration of indicators of growth and recruitment into a production characteristic, giving all indicators equal weight, gives weight to the attributes in relation to the number of indicators of each. In contrast to related indicators, this has not proved to be an important issue in applications to date. As above, it is best treated on a case by case basis.

Another possibility of double counting occurs when decision-making gives weight not only to the current status of an indicator but also to its trend over the recent period (as in Scotian Shelf groundfish assessments in 1999). Both these aspects of the indicator are pertinent to stock status assessment. However, in routine use of the Traffic Light method, prior year's estimates of an indicator will have already influenced the advice provided and the current level of TAC. Some experience with formulating decision rules should give insight into whether this is an issue of any importance.

As already noted, it is necessary to have documentation both of an attribute's relevance to the decision in question and the extent to which the proposed indicator provides a true measure of it, before an indicator is included in an analysis. However, neither of these matters is amenable to statistical quantification. In contrast, the precision with which an indicator is measured can be readily calculated in many (although not all) cases. Unfortunately, this last is arguably the least important of the reasons brought forward as bases for weighting.

It is well to keep in mind, when considering weighting, that the strength of the Traffic Light method is its ability to take into account a broad spectrum of information, qualitative as well as quantitative, which might be relevant to the issue in question. It would be counter-productive, therefore, to give high weights to the indicators that have been well researched, depended upon in previous assessments or that can be measured with high precision, while down-weighting information from new sources, or for additional attributes, which have less well established credentials. Weighting is a topic that can generate intense, prolonged and highly technical debate while adding little to the accuracy of the overall result. At least at the initial stages of constructing Traffic Light decision systems, debate could most usefully concentrate on the inclusion or exclusion of indicators, rather than the application of weightings.

Scaling

The discontinuous nature of the scaling when three lights are used is a disadvantage in that conversion of continuous variables into discrete categories results in the loss of information. This becomes a particularly contentious point when the Traffic Light method is applied in data-rich situations where other analytical methods are available that can more fully utilize the information available (although not necessarily for all available indicators). The sharp transitions between states present the perceptual problem that very small changes in an indicator can have major practical implications when observations are close to a boundary. The extent of this problem, in practice, depends on the integration method used. In Caddy's example, where the integration is based on the number of red lights, the scale of resolution of the integrated values is directly proportional to the number of indicators. Thus the problem is countered when there are a large number of indicators in use, as not all would be likely to change colour at the same time. Nonetheless, if the integration made is into a single green, yellow or red light, based on the predominance of colours in the indicators, fisheries could conceivably be closed and/or reopened based on minor data variations which are not, in themselves, meaningful.

This issue has been examined in some depth (Annex 3). In addition to the basic, or Strict, Traffic Light method in which data points can only have one of the three colours, two ways of introducing transition zones between colours have been considered. In one of the latter, transitional points were shaded between the end colours (termed the Ramp method), resulting in the use of more than three colours, and in the other (the Fuzzy Set method), transitional points were fractions of the neighbouring colours, and thus no additional colours were required. A continuous scaling system with, in theory, an infinite number of colours was also investigated.

Loss of information may occur during the conversions from data to indicators and during the integration of indicators to characteristics. In the conversion from data to indicator, the Strict Traffic Light is most affected by information loss. The Ramp and Fuzzy Logic are equally affected, if their transition zones between pure colours are the same size. The Continuous coding does not lose any information at this stage. During integration, the Strict Traffic Light is again most prone to information loss, with Ramp, Fuzzy and Continuous schemes being progressively less affected by this problem.

Although it is intrinsic to integration that some information is lost, the loss is not necessarily of practical importance. The original indicators are still available for decision rules that might require more information than is contained in the characteristics. Simplicity and communicability are issues of over-riding importance, and the virtually universal recognition of green, yellow and red as symbols for go, caution and stop, respectively, makes these colours highly effective tools for communication. This consideration favours the use of the Strict and Fuzzy methods, both of which utilize only three colours. The Fuzzy Set method has distinct advantages over the Strict method in retaining more information. The use of Fuzzy Sets for scaling and integration is examined using a hypothetical example in Annex 4.

Decision Rules

According to the precautionary approach, limit reference points should be used to trigger pre-agreed conservation and management action through decision rules (variously called harvest control laws or harvest control rules). Thus, decision rules specify how the management system will respond to estimated or perceived conditions in fish stocks, in the ecosystem, or in the fishery, relative to the reference points. An important aspect of the decision rule concept is that the decision-making criteria, e.g. what will be done if half the lights are red, are agreed upon and clearly articulated ahead of time. This allows the criteria to be decided upon in a rational and objective environment that should enhance the probability of farsighted decision-making.

The form of decision rules has yet to be adequately explored. Caddy (1998, 1999) provides one example of a decision rule based on Traffic Light scores (Fig. 1). There is also a Maritimes Region example of a formulistic decision rule based on the Traffic Light method. An arbitrary asymmetric proportional TAC adjustment procedure has been put forward for Scotian Shelf shrimp (Koeller et al., 1999). The asymmetric adjustment of TAC, downward adjustments being greater than upward adjustments, represents one option for building-in a precautionary approach. Such rules are likely adequate in data-poor situations but, when more data are available, more complex decision rules can be supported. Fuzzy Logic provides a tool for formulation of decision rules for more complex cases and a (purely hypothetical) worked example is described in Annex 5 to illustrate how fuzzy logic works. The operating assumption in these example decision rules is that the current state of the resource reflects the effects of recent catches and other factors and the near future will be similar in most ways to the immediate past.

The orientation in these examples is towards adjusting quantities removed (through adjustments to TACs or in fishing effort limits if any were in place) to maintain the productivity of stocks and, in particular, to restrict or eliminate fishing when bad things happen. Decision rules for the reopening of closed fisheries are necessary also, however, and these cannot be based on proportional adjustments of recent catches. Nonetheless, the methodologies should work equally well for formulating appropriate rules for managing stocks out of unacceptable states. These rules also could be readily modified to take into account recent trends if this was thought to be desirable. However, it would first be necessary to devise criteria for assignment of lights to trends and to decide what weight should be given to these relative to the last observation. These are not matters given any amount of consideration to date.

The example decision rules referred to above are similar to those used currently (based on other assessment models) in that they translate biological information on stock status directly into catch (or fishing effort) limits. This rule formulation is over-simplistic, however, as the biological inputs that form the basis for stock status determination do not represent the full range of information that should be taken into account in TAC determination. A multi-level, or nested, decision making structure is required with stock assessment, ecosystem, socio-economic and compliance components. Decisions for each element must be made conditional on decisions for other elements, so that the resulting plan has logical integrity. For example, if F is above the specified level but indicators of compliance with catch limits suggest that compliance is low, the appropriate corrective action may be to increase enforcement, as reducing the TAC would be likely to have little or no effect on F. Reducing ecosystem effects of fishing could be addressed through reduction of fishing effort for the directed species (by reducing the TAC). However, season/area closures, banning particular gear types or configurations, or improving gear selection may offer more cost-effective solutions. Such inter-related decision rules can only be effected in the context of integrated fishery management plans.

The formulation of decision rules needs to involve all interested parties. Decisions on resource conservation must involve scientists, as it is scientists who have the expertise to define biological limits, but are not solely their responsibility. Science output must make clear where stock status lies in relation to limit reference points and provide guidance as to the urgency and scope of actions required to avoid (or recover from) unacceptable outcomes. When resources are not close to danger zones, however, the industry and fishery managers should be the primary determiners of annual catch levels. In mixed fishery situations, this flexibility would allow more scope to manage bycatch problems and reduce discarding and promote more efficient and thus more economical harvesting.

DISCUSSION

This document is very much a progress report. The intention of the work is to evaluate the Traffic Light method as the technical foundation for fishery management planning, but its scope to date has been largely restricted to application of the method to stock assessment. All the problematic issues raised by trial applications of the method in this context have been evaluated and suggestions are put forward for their solution. There is no intention to suggest, however, that there is any broad consensus of opinion on these solutions. Indeed, there remains considerable controversy about appropriate techniques for both boundary determination and integration.

A move to full scale application of the Traffic Light method for stock status assessment is a next logical step, as continuing development of the methodology requires the insights obtained from use. This has been so for all new methodologies. Development of the SPA/catch projection method in the late 1960s immediately supported the introduction of TAC regulation on an Atlantic-wide basis. After 30 years, its capabilities and limitations are still matters of controversy. At the present time a methodology is needed to support the introduction of the precautionary approach. We are encouraged to think that the Traffic Light method can provide the framework for this.

By taking into consideration a wider range of factors than traditional assessment methods, the Traffic Light precautionary decision framework, reduces the risk of missing important stock dynamic, environmental or ecosystem signals, i.e. it depends on a multiplicity of limit reference points. It does not require that previously used analyses be abandoned. On the contrary, if their outputs are still considered useful, they can be incorporated into this more general framework. This broadening of the basis for stock assessment has the result of refocusing attention on the biology of the resource and on the environment and ecosystem of which it is part, rather than on ever more sophisticated statistical methods for analyzing low grade fishery data.

A particularly strong argument in the method's favour is its virtue of simplicity. A transparency in the methodology used to reach conclusions allows stakeholders to understand the evidence put before them. Furthermore, the method can easily accommodate the direct observations of fishermen. These features promote industry acceptance of results and generate support for the taking of actions that cause (at least short-term) hardship. Risk of resource depletion is reduced if the fishing industry is supportive of conservation measures.

The form of decision rules is only beginning to be addressed but this is difficult to do except in practical situations. Nonetheless, formulating appropriate rules for action represents the most important part of constructing a precautionary management decision framework (Caddy, in press). As already noted, this is largely a job for stakeholders and managers (and in the case of Atlantic groundfish, the Fisheries Resource Conservation Council), rather than scientists. It would be fruitful now to try applying the method in overall management planning. The Objective-Based Fisheries Management initiative pilot applications present such an opportunity. The method has potential also as a decision framework in management at the ecosystem level.

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ANNEX 1.

Glossary

Attribute: A conceptual property of fish stocks, e.g. biomass, or fisheries, e.g. employment, which describe their status. Indicators provide estimates of attributes.

Boundary: a data value that defines the limit of Traffic Light colours or, graphically, the line that demarcates green from yellow or yellow from red. Boundaries can be chosen so that they equate to reference points, but can also be set according to other criteria.

Characteristic: A conceptual entity, e.g. abundance or production, based on an aggregate of similar indicators, which is used for further analysis or in formulation of decision rules.

Decision Rule: A pre-agreed relational statement that associates a specific management action or actions with a specified outcome of an analysis of stock and/or fishery status.

Fuzzy Set: The basis for fuzzy, or multivalent logic in which statements can be true to some degree and false to a complementary degree, e.g. a data point can be part yellow and part red. (In classical sets, the foundation of classical, or bivalent logic, statements are either true or false, i.e. a data point can only be all yellow or all red.)

Indicator: A product derived from data that gives information about the state of an attribute, e.g. mean weight per tow of cod gives an indication of cod biomass. Most indicators are based on time series of data. Sometimes, several indicators may be available for a particular attribute.

Integration: The combining of indicators to provide a summary index. This summary may be at the level of a characteristic or be for all indicators.

Performance Measures: A class of indicators that can be influenced by managerial intervention and thus can be used to measure organizational success in program delivery. Fishing mortality is an example of such a 'control' indicator. 'State' indicators, such as those measuring growth or environmental conditions, are not influenced by regulatory actions.

Reference Point: A technical basis for operationalizing the general objectives of management. There are two types, target and limit. A **target reference point** defines a condition that it is considered desirable to achieve, e.g. $F_{0.1}$. A **limit reference point** defines an unacceptable outcome, e.g. a particular stock biomass considered to be too low.

Weighting: The giving of different importance to some indicators when integrating into characteristics. The most important reason for this put forward so far is that some indicators are inter-dependent, i.e. are derived in total or part from the same data, and that this amounts to 'double-counting' of the underlying data.

Scaling: The assignment of lights to indicator values to normalize data series prior to integration. The amount of information loss due to scaling depends on the method used.

ANNEX 2.

Template Outlining the Sections of a Traffic Light Indicator Account

Indicator: Descriptive name of indicator, including short form used on Traffic Light output.

Characteristic: Name of the characteristic of stock status the indicator reflects. Current choices include **Abundance**, **Production, Fishing Mortality** and **Ecosystem/Environment**.

Description: Describe the attribute being measured by the indicator and the scientific basis underlying its relationship to one or more characteristics. Describe also, if necessary, how the indicator relates to the attribute.

Boundary Point(s): Basis for setting boundary points between colour ranges. Although statistics based on historical data series have been widely used it is preferable that some external basis for determining the ranges be applied, especially in cases where there is a short data series or little dynamic range in the data. Intercalibration of data series may be an option in some cases.

Properties:

Estimation:
- data source(s)
- range selections
- computation including transformations, smoothing etc.
- availability and location of software for calculation of the indicator

Measurability:
- statistical properties of estimator e.g. variability, bias, skewness
- transformations if required
- standard or alternative formulations for estimator, if non-standard, why?
- consistency with other estimators of indicator

Interpretability:
- how does this indicator reflect stock status or the identified characteristic?
- what caveats exist?
- how well are the colour boundaries related to changes in stock status or characteristic?

Sensitivity:
- how rapidly does indicator respond to changes in stock status?
- is there adequate time for management interventions?

- is the natural variability likely mask real changes?

Weight:

The overall value of an indicator, on a scale relative to the other available indicators. This is based on primarily on the strength of the individual attributes and the qualities of the proposed reference points. At least four types of uncertainty have been identified:

1. Statistical uncertainty due to sampling error in the indicator related to measurability
2. Boundary point uncertainty related to interpretability
3. Importance of the indicator, again related to interpretability
4. Structural uncertainty, the sensitivity of the indicator to changes in the formulation of the estimator.

Review of Performance or **Validation of Indicator:**

If data exists, an assessment of the performance of the indicator over a time series of estimates is desirable. An alternative approach would be to validate the indicator and boundary points against external information e.g. $F_{0.1}$ or critical values for fish condition. In either case the review must demonstrate the adequacy of the indicator, its estimator and the selected boundary values.

ANNEX 3.

Examination of Scaling Methods

In addition to the basic or "Strict" Traffic Light method, "Continuous" scaling and two ways of introducing transition zones between colours, labelled the "Ramp" and "Fuzzy" set methods, have been investigated. In contrast to the Strict, three light, method (Fig. 4a), the Ramp Traffic Lights have transition zones between colours that, for simplicity, are shown as linear ramps in Fig.4b. For this scheme, four decision points are needed: end of green, start of yellow, end of yellow and start of red. In the transition zones the colours are shaded between the end colours, resulting in the use of more than three colours. The Fuzzy method (Fig. 4c) uses the same four decision points as the Ramp Traffic Lights. The distinction is that the transitions are fractions of the neighbouring colours, and thus no additional colours are required. That is, mid way between yellow and red is half of each colour, whereas it was shown as orange in the Ramp system. Unlike the previous three, the Continuous scaling system (Fig. 4d) has no flat areas in the scaling and in theory an infinite number of colours would be required. (The display in Fig. 4d has 30 colours.)

The consequences to the results of integration to the characteristic level of applying these scaling methods were examined (Fig. 5). A set of test data was constructed for four indicators that consisted of time series for 1970-80. The Strict Traffic Light assigned a value of 0, 0.5 and 1 to green yellow and red respectively. The integration in this system is by averaging the number values for each colour. If the average is less than 0.33 green is assigned, if in the range 0.33-0.67 yellow is assigned and if above 0.67 red is assigned. In this example most of the time the characteristic is yellow (Fig. 5a). Integrating in the Ramp Traffic Light system requires the definition of transition zones for the characteristic as well as for the indicators. Again the indicators are simply averaged and then compared to a set of four decision levels. In the example the green-yellow transition for the characteristic is from 0.28 to 0.38 and for yellow-red 0.62 to 0.72. As in the Strict example, yellow dominates but shades can be seen, especially in the most recent years (Fig. 5b). The Fuzzy Logic example simply adds up the individual indicators and no decision levels are required for the characteristic. For example the 1970 data had three indicators which were green and one which was red. The characteristic is thus 75% green and 25% red (Fig. 5c). The Continuous integration is similar to the Fuzzy approach except that there are more than three colours (Fig. 5d). Arbitrarily, a resolution of 0.0001 was used to aggregate the Continuous indicators, i.e. indicators closer than 0.0001 were considered to be the same colour. After aggregation, this fine scale of resolution was rounded to the 30 steps of colours used for display.

The conversion of data into indicators has two steps, normalization and colouring. In these examples the normalization was from 0 to 1 for all four schemes but the colours were different for each. The Ramp and Fuzzy Logic approaches used the same decision points but assigned colours differently. In these two examples the indicators from either system (Ramp or Fuzzy) are completely interchangeable.

Information may be lost during the conversions from data to indicators and during the integration of indicators to characteristics. In the conversion from data to indicator, the broader the solid colour zones, the more information will be lost. Once you are in a red zone there is no discrimination as to where you are within it. The Strict Traffic Light is most affected by this loss. The Ramp and Fuzzy Logic are equally affected, if their transition zones between pure colours are the same size. The Continuous coding does not lose any information at this stage. During integration, the Strict Traffic Light is again most prone to information loss; it is impossible to tell if a yellow characteristic was the result of the mixing of a red and green or the sum of a number of yellow indicators. The Ramp similarly suffers at this stage. The Fuzzy integration can distinguish between these inputs, but cannot distinguish between the integration of a red and a yellow and the sum of two indicators both of which were half red and yellow. Integration within the Continuous scheme is least affected by this problem as, with more colours, it is more probable that the information will not be lost.

ANNEX 4.

Indicators as Fuzzy Sets

One way of assigning the traffic light colours to a given indicator is to consider the colours as the names of sets describing the data values in the set. Thus saying that a given value of an indicator is green says that it lies in the set 'green'. The Strict Traffic Light corresponds to the classical set, which says that a value is either in the set 'green' or it is something else, i.e. 'not-green' and it cannot be both. Of course the same reasoning applies to all three colours and, assuming all possible values of the indicator have been assigned to a colour, any given value is restricted to being in one, and only one, colour set. In fuzzy sets this is not so. A given value of an indicator can belong, to some degree, to more than one colour set. The degree of membership in all sets must sum to 1.0, that is, if an indicator value has a membership in 'green' of 0.8 it has a membership in 'not-green' of 0.2. In this case 'not-green' corresponds to the sum of the membership in 'yellow' and 'red'. Thus classical sets (or crisp sets) are a subset of fuzzy sets for which Aristotle's law of the Excluded Middle is invoked and membership can only be to degree 1 or 0.

Classical sets are the foundation of classical or bivalent logic in which statements are either true or false, there is no middle ground. Fuzzy sets lead to fuzzy or multivalent logic in which statements may be true to some degree and false to a complementary degree. Fuzzy logic is in turn the basis of fuzzy control theory, which provides a systematic means of defining and evaluating decision rules.

The determination of Traffic Light boundaries discretizes a continuous indicator into a simple three-state variable i.e. defines three sets. In reality, there are no sharp boundaries between levels of red and yellow or yellow and green. A better representation of the boundaries is obtained by treating the different colours as fuzzy sets. In this case, the indicator represents a degree of red, yellow or green and any given level will include all three colours to some degree, possibly zero. Consider a well studied indicator such as survey abundance (Fig. 6). Values above the mean, say 30,000, can be considered in a green state with reasonable confidence. However it is not clear that a value very slightly less than the mean, say 29,000, has changed enough to indicate that a yellow or cautious condition exists. In fact, the overall condition is still essentially green, however a small degree of yellow is now warranted. In fuzzy logic terms, the indicator belongs to the set green to a large degree and the set yellow to a small degree (and the set red to 0 degree). An additive rule in fuzzy sets requires that for any given value, the degrees of membership in the fuzzy sets sum to one. That is, although a given value can belong to more than one set, in sum it must belong wholly to the domain (set of all sets). Representation of the fuzzy membership functions as piece-wise linear (triangles or trapezoids as used in this example) is a simplification that is rarely optimal when sufficient data exist to determine an optimal shape. In spite of that, it is an extremely useful representation and performs as well as most alternatives in situations, such as fisheries, where criteria for defining boundaries are poorly developed. The triangles can be translated to adjust the boundaries or they can be asymmetric indicating that there is greater uncertainty in one boundary than in the other. Trapezoids (shown at the extremes in these examples) can also be used in central sections where ranges of non-fuzzy indicators exist. This last is not likely in fisheries applications. Although there is no mathematical restriction on the number of fuzzy sets co-occurring at a given point, the Traffic Light sets will be restricted to a maximum of two co-occurring colours. This restriction simply states that red and green cannot overlap in the ordered sets of red/yellow/green defined for the Traffic Light method.

Graphical representation of fuzzy Traffic Light sets is a bit more complicated than in the Strict method. More than one colour needs to be included in a given indicator light. Two possibilities are to structure the indicator as a pie chart or as a bubble chart (the latter option gives the appearance of a traffic light). In the examples shown (Fig. 7a), the values of 29000 and 14000 are taken from the fuzzy indicator above. In the first instance the value is slightly below the green/yellow boundary. In the case of a Strict set with sharp boundaries, the indicator would be yellow. In the fuzzy case, crossing the boundary has resulted in a small degree of yellow being reported. The second example is a value below the yellow/red boundary. In this instance the indicator includes mostly yellow but with a large fraction of red as well. In the extremes (>30000 or <6000) there is no uncertainty and hence no fuzz, the indicator is all green or all red, respectively. If differing weights were assigned to different indicators, the weights given could be represented by differing sizes of pie or bubble charts. However, differences in size are not as readily visible in the bubble chart case.

A third alternative (W. Silvert, pers. comm.) represents the traffic lights as stacked bar charts, i.e. rectangular 'lights' (Fig 7b). In this case the relative weights of different Traffic Light sets can be easily seen. The examples here show a two-fold difference in weights and a two-light versus three-light set. Although indicators are restricted to two colours at a time, the results of integrating multiple indicators will often show all three colours (see Characteristics below).

A characteristic needs to preserve all the colour information of the relevant input indicators. Because the indicators within a characteristic are all believed to be reflections of the same thing they can be integrated by a simple integration of the colours. In this instance a simple summation of the total area of each colour, renormalized to sum to 1.0, will preserve both the amount of each colour present in the indicators and the relative weights that may have been assigned them. Independent weighting can be applied to multiple characteristics in subsequent uses.

In the hypothetical example illustrated in Fig. 8 there are three characteristics, production, fisheries (impact on the ecosystem) and cod stock, integrated from three, two and two indicators respectively. The characteristics are given equal relative weight, but the spawning biomass indicator has twice the weight of the rest of the indicators. This is reflected in the fact that the cod stock characteristic shows over ¾ yellow (from SSB) and less than ¼ red (from juvenile mortality). The production characteristic reflects inputs from three indicators and the disparity between the March and July Fulton's K is reflected in the presence of both red and green in this characteristic. Because the characteristics are results of fuzzy set integration, they are already fuzzy and there is no requirement to specify the shape and values of the fuzzy set definitions. A set of fuzzy characteristics such as this (but using validated data, of course, as opposed to the present contrived example) would be the basis of a stock or fishery assessment, integrating all data-based indicators and model-based results into a single framework of information.

ANNEX 5.

An Example Fuzzy Logic Traffic Light Decision Framework

Fuzzy Logic provides a tool for formulation of decision rules for more complex cases and a worked example is described below to illustrate how fuzzy logic works. This example is purely hypothetical. The characteristics developed in Annex 4 (Fig. 8) are used here as input to a precautionary decision framework based on feasible fuzzy control decision rules. The single output variable is implemented as an increment (positive or negative) of the current TAC. The operating assumption in the example is that the current state reflects the effects of recent catches (and other factors) and the near future (next year) will be similar to this year in most ways, i.e. the best predictor of tomorrow's weather is today's weather. There are many ways to improve the implicit projections within this framework but they are not pursued here.

In fuzzy control systems each rule in the system is evaluated on each iteration and its' contribution (fuzzy implication) to the final output determined. Fuzzy rules are all of the form 'IF x THEN DO y', similar to a conventional IF statement in logic. The fuzzy form is perhaps better read as 'TO THE DEGREE THAT x IS true, INCLUDE y IN THE OUTPUT'. Thus every rule is included but in some cases it may have 0 contribution to the output, i.e. x is not true to any degree. The rule system used in the example includes the following nine rules:

IF fisheries = green AND production = green AND stock = green THEN tac_increment is

large positive

IF production = green AND stock = green THEN tac_increment is small positive

IF production = green AND stock = yellow THEN tac_increment is no change

IF production = green AND stock = red THEN tac_increment is small negative

IF production = yellow AND stock = green THEN tac_increment is no change

IF production = yellow AND stock = yellow THEN tac_increment is small negative

IF production = yellow AND stock = red THEN tac_increment is large negative

IF production = red AND stock = green THEN tac_increment is small negative

IF production = red AND stock $\neq$ green THEN tac_increment is large negative

The output given by this system of rules is in the form of degrees of membership (≡ truth) of the TAC increment in five fuzzy sets (Fig. 9a). The sets cover the range [-1,1] and are called 'large negative' (black), 'small negative' (red), 'no change' (yellow), 'small positive' (green) and 'large positive' (blue) in order over the range. An increment of -1.0 would imply reducing the catch (or TAC) to 0 while 1.0 would imply doubling. These output sets are fuzzy. For example, a small positive increment (represented by the green set) covers any positive value to some degree, peaking at 50% increase. These sets are used in the next step of 'defuzzifying' the result to determine the actual control action to take.

Evaluating the nine rule system and the fuzzy characteristics given above results in the output sets shown in Fig. 9b. The degree of membership for the sets 'small positive' and 'large positive' are both 0 simply because the rule system (rules 1 and 2) requires that both stock size and production be green to produce a positive increment. In the example, the cod stock size is yellow and red and so no positive increments are indicated. In spite of that there is still a component of the output on the positive side of the axis since the set 'no change' includes all values between -0.5 and +0.5 to varying degrees. Given that more than one rule may imply a value for a given set, the combined result is the maximum value for the set. In this example, the set 'large negative' has a value of 0.34, 'small negative' is 0.18 and 'no change' is 0.55. In all cases where sets overlap, the greater value is used. For example, the 'no change' set is triggered as a result of two rules (3rd and 5th) in the preceding rule set. Rule 3 triggers the set 'no change' to the degree that the production characteristic is green and the stock characteristic is yellow. In this example, production is green is true to 0.55 degree while stock is yellow is true to 0.7 degree. Thus they are both true to the lesser degree, i.e. 0.55, which becomes the degree to which this rule triggers the 'no change' set. The fifth rule reverses the two colours with respect to the characteristics. In this instance, production is yellow to about 0.1 degree and stock is green to about 0.17 degree, which triggers the 'no change', set to 0.1. Combining the effects of the two rules the set is triggered to the greater of the two values, i.e. 0.55, which is represented by the height of the shading inside the triangle defining the set.

Once all the decision rules have been evaluated a fuzzy set of outputs has been defined. The fuzzy set now needs to be transformed into a specific, i.e. crisp, output response through a process of defuzzifying. There are a variety of options for this process although only one, the centroid method, is used here. The centroid is the centre of mass of the output sets, i.e. the point on the abscissa to either side of which the included area in all sets is equal. The indicated result is that the TAC increment should be -17% (Fig. 9c). A fuzzy controller such as this is not statistical and does not routinely use estimates of uncertainty in the output value. Because we are considering a system to provide input to a further control system (fisheries management) there is considerable value in being able to characterize the precision of the control output. To assess the uncertainty associated with that value, the root mean squared (RMS) error is provided as an analogue of a standard deviation. The graph lines indicate ±1 (thick line) and ±2 (thin line) RMS errors.

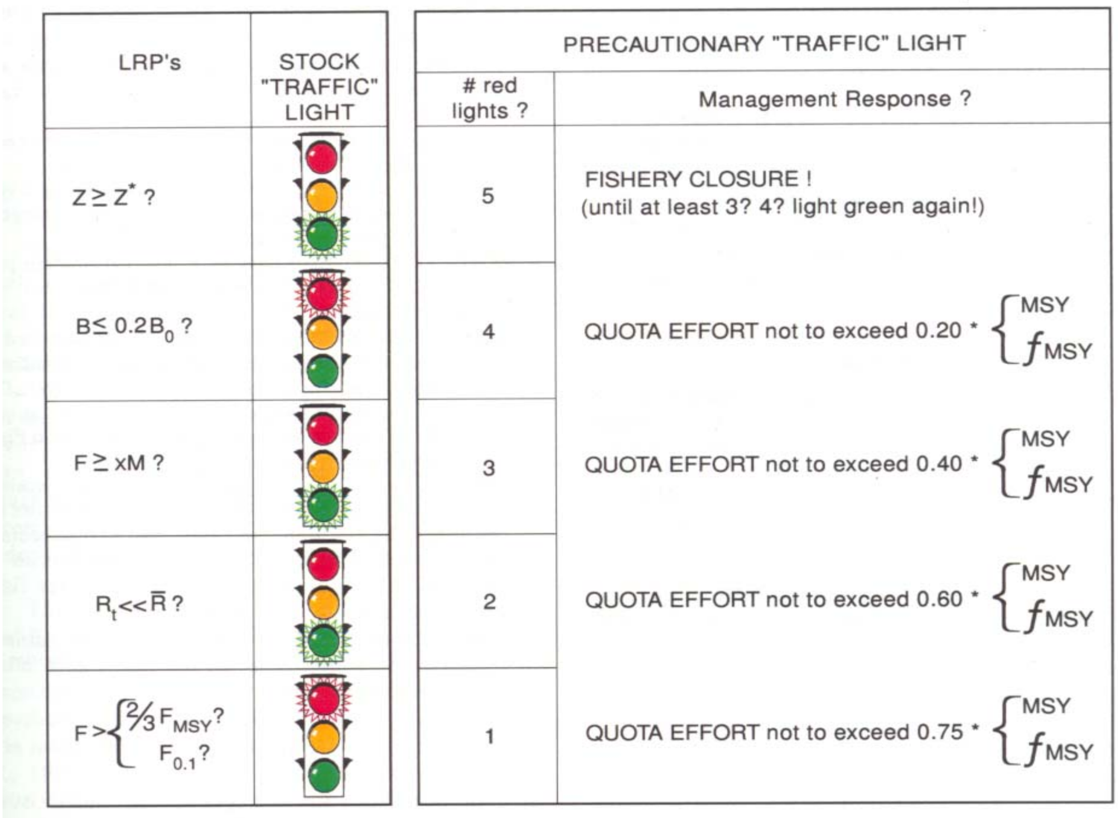
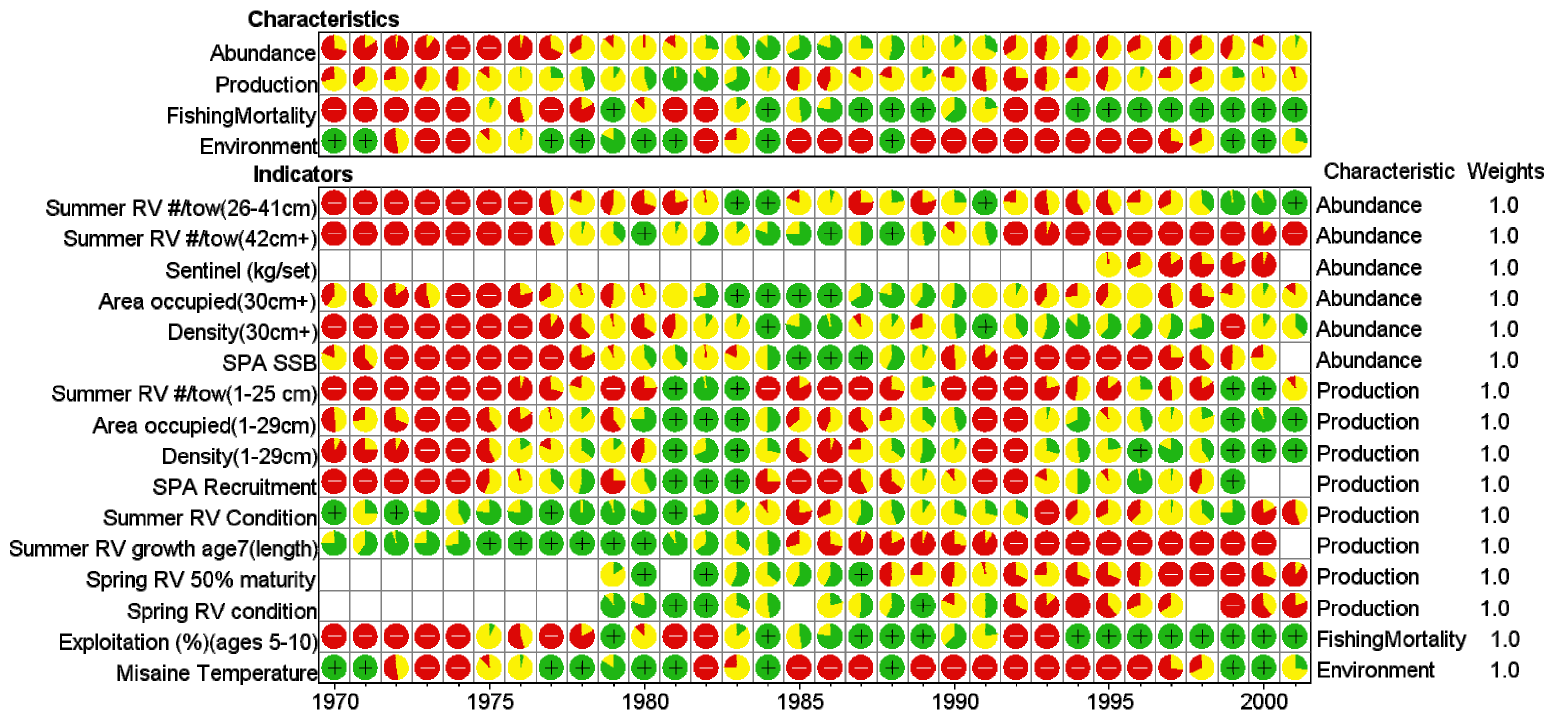


Fig. 1. Caddy's illustration of a Traffic Light decision framework (Caddy, 1999: Fig. 3).

YEAR	PREDATION	RECRUITMENT	POPULATION ABUNDANCE	FISHING PATTERN	FISHERY PERFORMANCE	EXPLOITATION	SUMMARY
1990	--	--	+	+	+	+	0
1991	--	--	0	+	0	+	0
1992	0	--	--	0	--	--	--
1993	0	0	--	0	--	--	--
1994	+		0	0	0	0	0
1995	+	+	+	+	+	0	+
1996	+	+	+	+	+	0	+
1997	+	+	+	+	+	+	+
1998	0		+	0	+	+	0

Fig. 2. Retrospective analysis (summary of performance reports) for Sept Îles area in the Gulf of St. Lawrence for 1990-1998 (from Koeller et al., 2000).

Fig. 3. Traffic Light table for Div. 4VW haddock agreed to as the basis for stock status advice at the groundfish RAP meeting of November 2001.



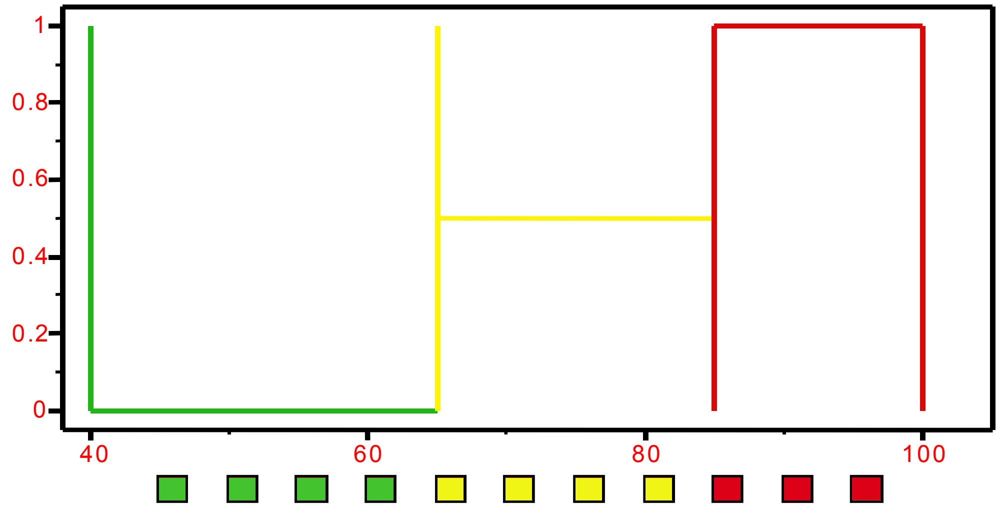


Fig. 4a. Schematic for Strict Traffic Lights. Light assignments for arbitrarily selected values are shown below (squares rather than circles used for convenience only).

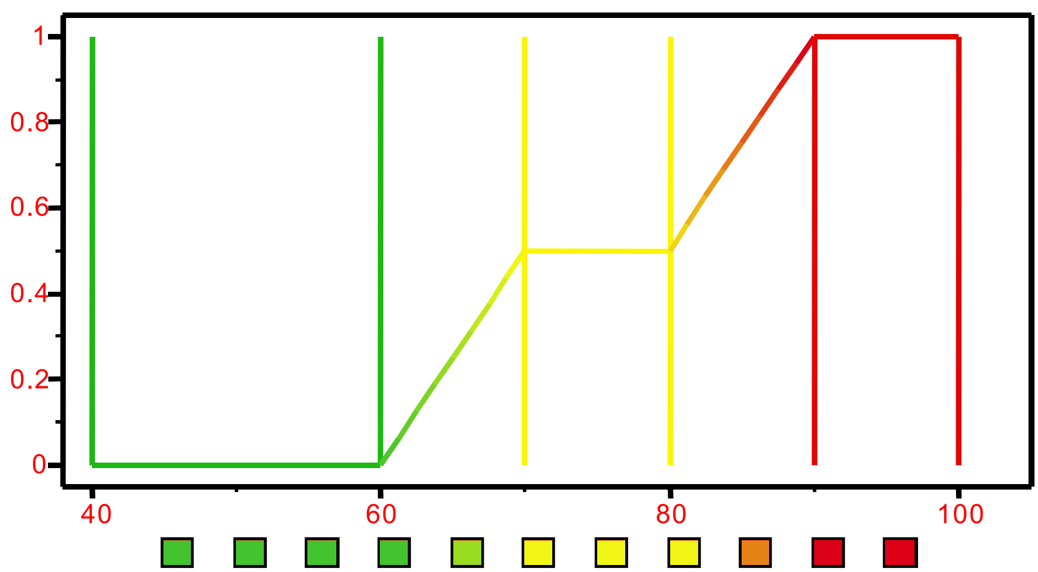


Fig. 4b. Schematic for Ramp Traffic Lights. Light assignments for arbitrarily selected values are shown below (squares rather than circles used for convenience only).

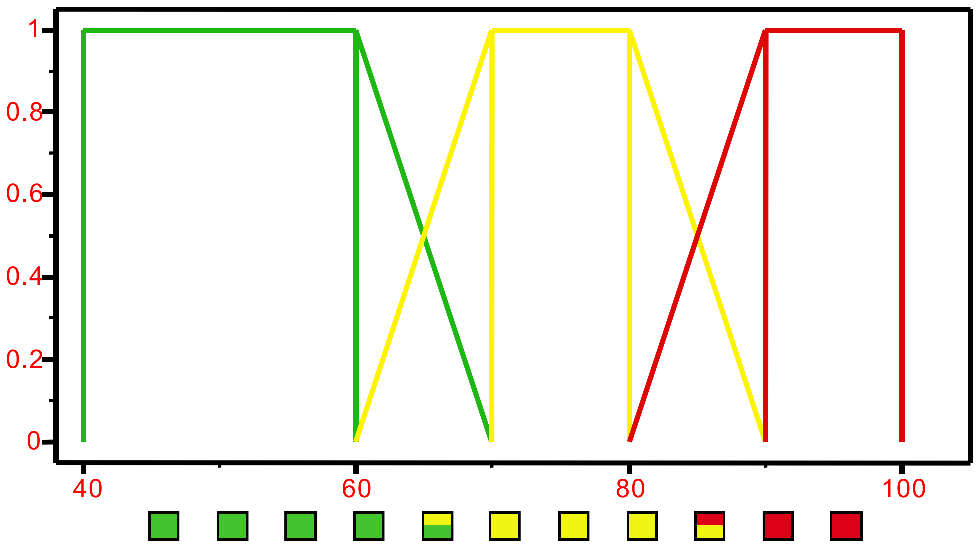


Fig. 4c. Schematic for Fuzzy Traffic Lights. Light assignments for arbitrarily selected values are shown below (squares rather than circles used for convenience only).

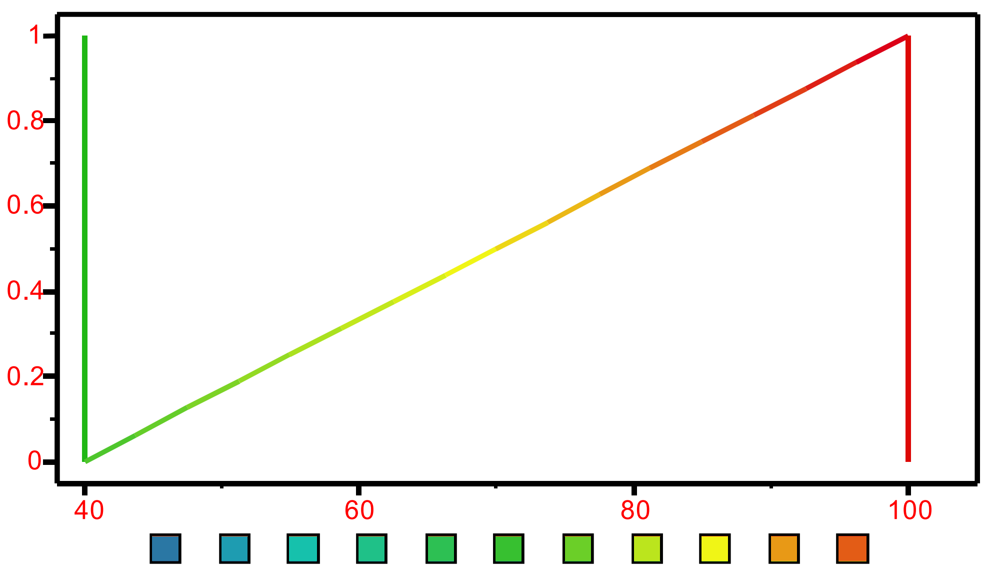


Fig. 4d. Schematic for Continuous Traffic Lights. Light assignments for arbitrarily selected values are shown below (squares rather than circles used for convenience only). (Although the figure should have the sloping line range over all colours, starting at violet instead of green on the left, this is prevented by technical limitations.)

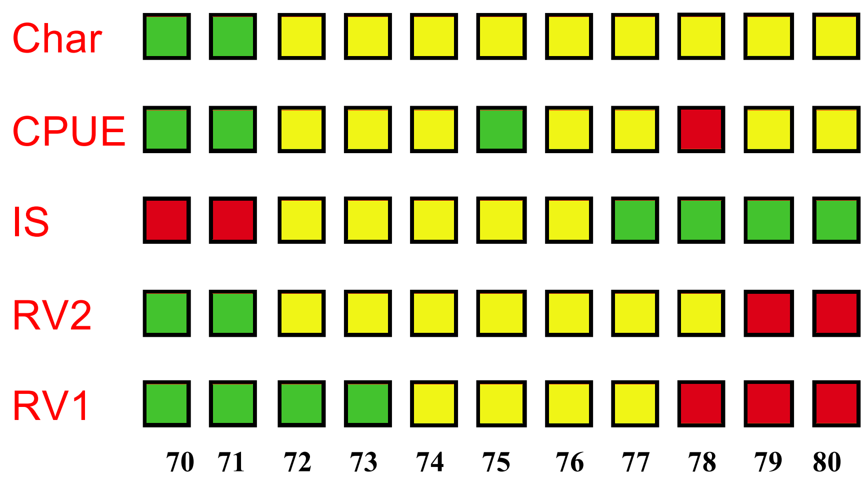


Fig. 5a. Strict Traffic Light table. (Char – integrated summary, other rows are indicators.)

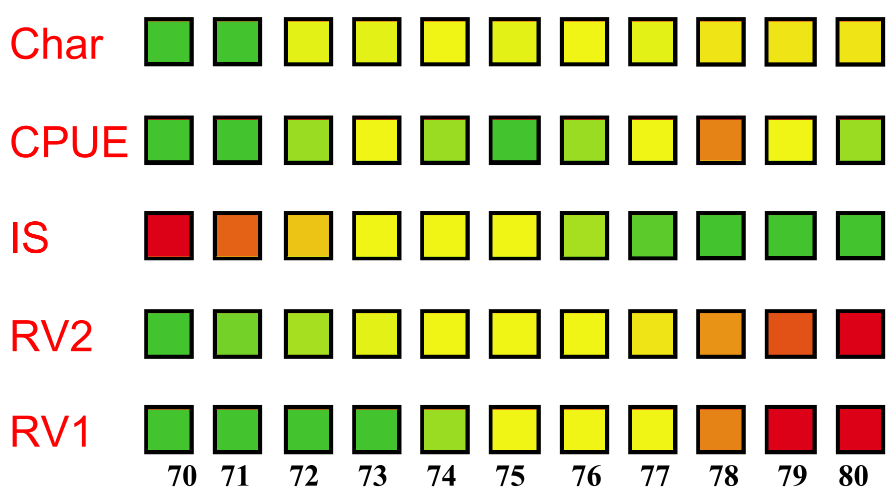


Fig. 5b. Ramp Traffic Light table. (Char – integrated summary, other rows are indicators.)

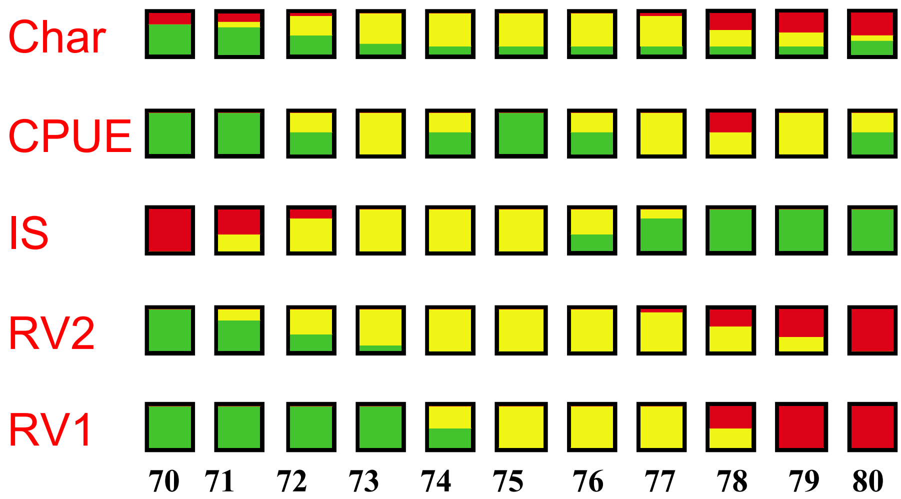


Fig. 5c. Fuzzy Traffic Light table. (Char – integrated summary, other rows are indicators.)

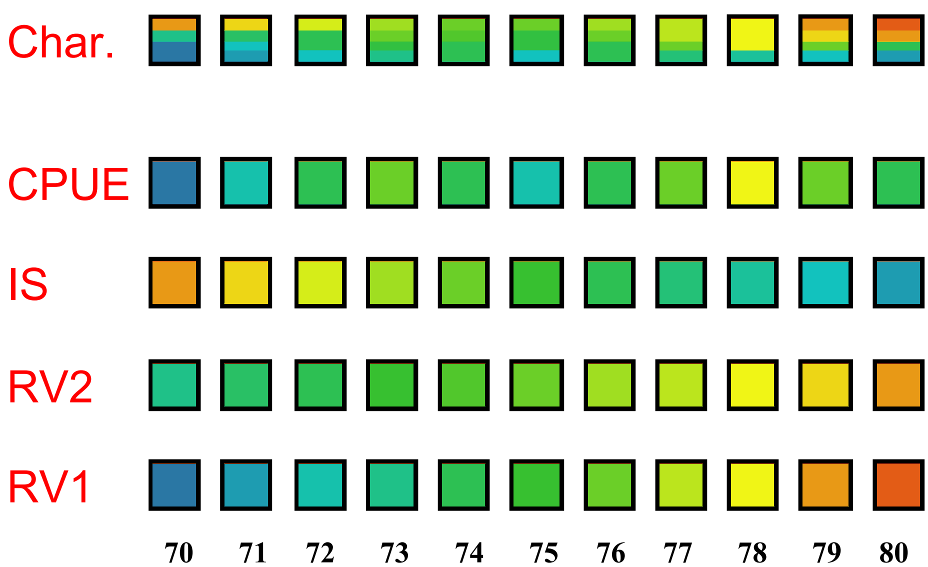


Fig. 5d. Continuous Traffic Light table. (Char – integrated summary, other rows are indicators.)

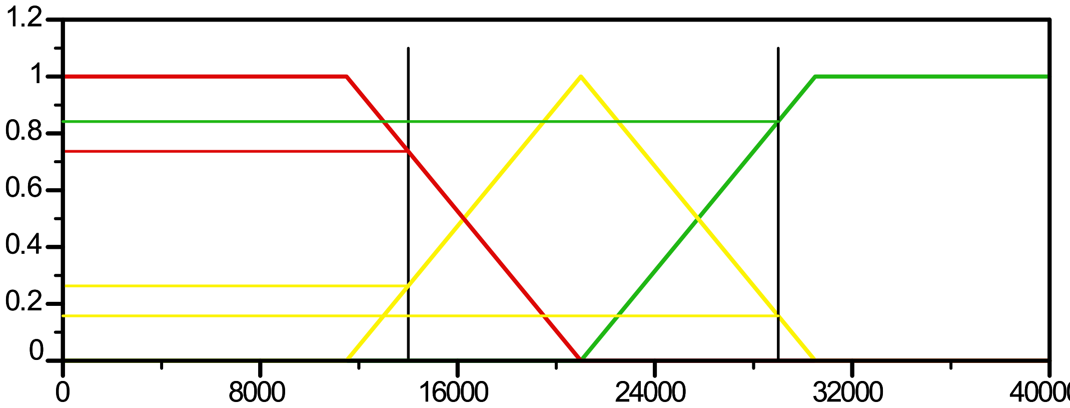


Figure 6. Fuzzy set traffic light definitions for the indicator values 14000 and 29000

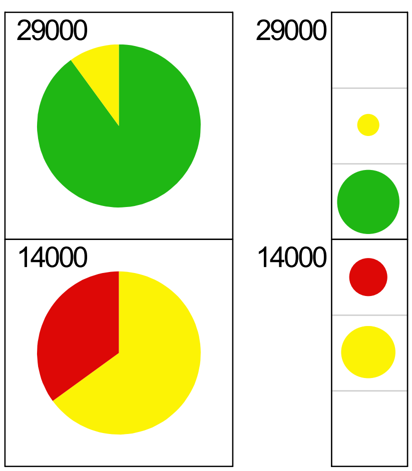


Figure 7a. Representations of fuzzy traffic lights as pie charts(left)
and bubble charts (right).

Figure 7b. Representations of fuzzy traffic lights as bar charts showing
different weights and 2 or 3 colour lights.

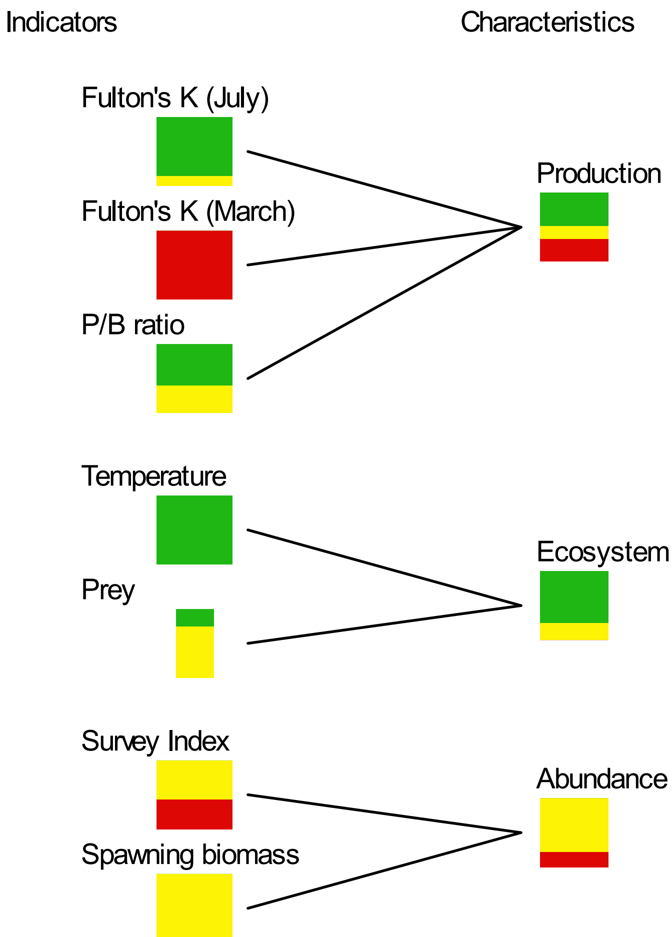


Figure 8. Fuzzy integration of indicators into characteristics (note reduced weight for prey indicator

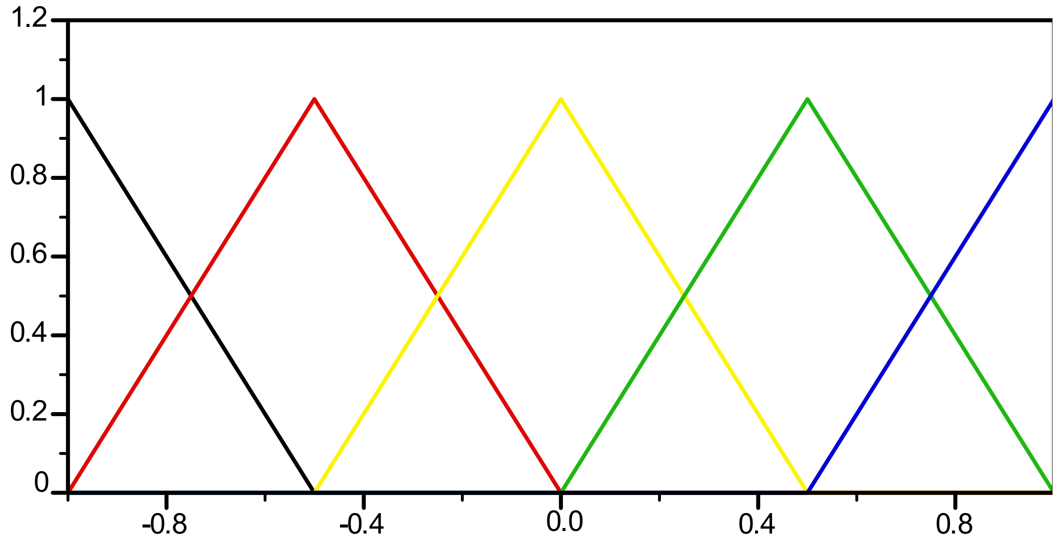


Figure 9a. Definition of output sets for the TAC adjustment

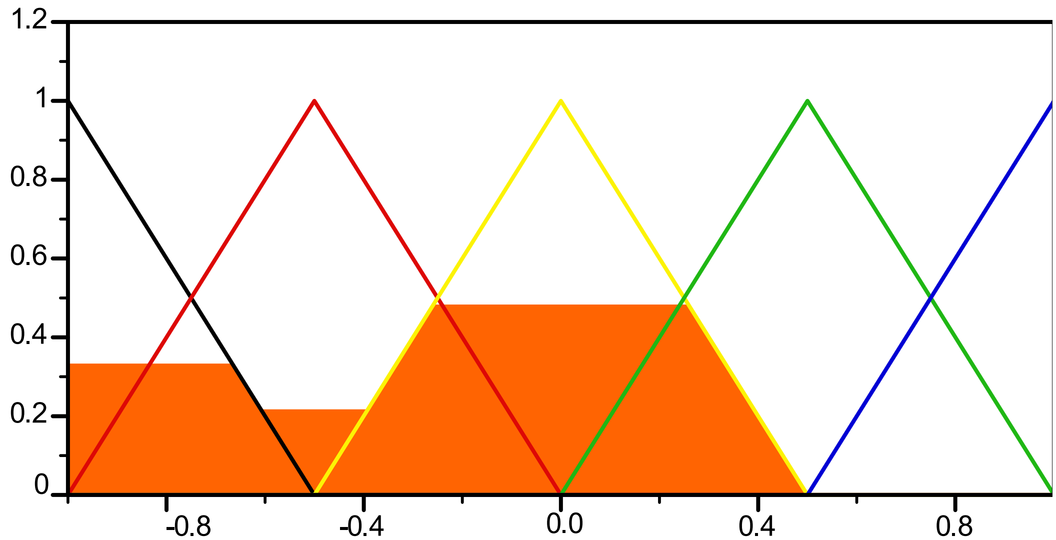


Figure 9b. Evaluation of decision rules show degree of each output as filled area

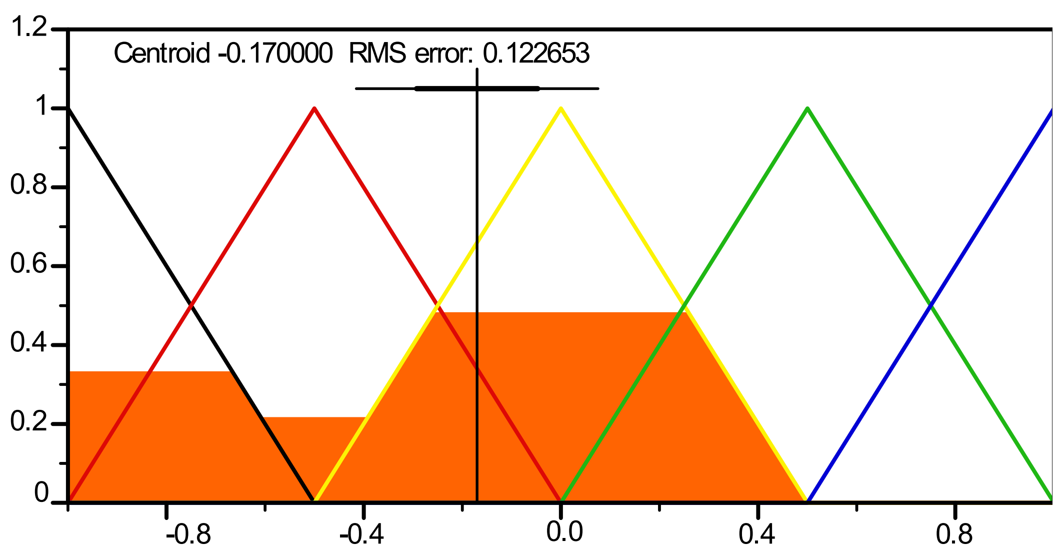


Figure 9c. Defuzzification of output sets yields TAC adjustment of 17% reduction