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CALCULATING NET CHANGE OF PRODUCTIVITY

OF FISH HABITATS

by

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ABSTRACT

Minns, C.K., 1995. Calculating net change of productivity of fish habitats. Can. MS Rep. Fish. Aquat. Sci., 2282:vi+37p.

Interpretation of the Policy for the Management of Fish Habitat (DFO 1986) and especially of its guiding principle, '*No Net Loss of Productive Capacity of Fish Habitats*', suggests that a less than absolute approach is required to produce a workable policy. Basic terms are defined: production, productivity, and productive capacity. The existing definition of productive capacity appears to automatically preclude most development. An alternative guiding principle is proposed for the policy: '**No net loss of the natural productivity of fish habitats**'. A quantitative framework for measuring net change of productivity is presented. Three options for estimating net change are identified, depending on how habitat loss and modification are treated with respect to changes in productivity per unit-area. Stringent definitions of net change based on maximum productivity (i.e., productive capacity) allow little scope for development as virtually all changes will incur a net loss of productivity. Using only the current productivity conserves and protects little, if any, of the natural productivity of fish habitats. The recommended compromise option charges habitat loss at the maximum productivity per unit-area and modified habitat at the current value with the requirement that there be a net gain of productivity. The compromise option has a built-in development limit. Relaxing the initial framework assumptions does not affect the use of the net change equation. Potential obstacles to the everyday use of the calculation framework are assessed. The net change equations can be integrated into existing procedures for assessing developments which might destroy fish habitat as required under the Fisheries Act. Existing qualitative steps can be expressed as quantitative tests.

SOMMAIRE

Minns, C.K., 1995. Calcul du changement net de la productivité des habitats du poisson. Rapport manuscrit canadien des sciences halieutiques et aquatiques 2282:vi+37p.

L'interprétation de la Politique de gestion de l'habitat du poisson (MPO, 1986) et particulièrement de son principe directeur, *«Aucune perte nette de la capacité de production des habitats»*, permet de penser qu'il faut adopter une approche qui n'ait pas un caractère absolu si on veut qu'une telle politique soit applicable. Les termes de base (production, productivité, capacité de production) sont définis. La définition actuelle de la capacité de production semble interdire automatiquement la plupart des projets de développement. Nous proposons une nouvelle formulation de ce principe directeur : **«Aucune perte nette de la productivité naturelle des habitats»**, et nous présentons un cadre quantitatif pour mesurer le changement net de la productivité. Trois options sont proposées pour estimer ce changement net selon la façon dont la perte et la modification de l'habitat sont traitées par rapport aux changements de la productivité par unité de surface. Les définitions strictes du changement net fondées sur la productivité maximale (c.-à-d. la capacité de production) laissent très peu de place au développement car presque toutes les modifications occasionnent une perte nette de productivité. Le fait de ne retenir que la productivité actuelle conserve et protège bien peu, sinon rien, de la productivité naturelle des habitats. L'option de compromis recommandée calcule la perte d'habitat au maximum de productivité par unité de surface et la modification de l'habitat à sa valeur actuelle tout en exigeant qu'il y ait un gain net de productivité. L'option de compromis porte en elle-même une limite au développement. Le fait d'assouplir les hypothèses-cadres de départ n'affecte pas l'utilisation de l'équation concernant le changement net. Nous évaluons les obstacles potentiels à l'emploi courant du cadre de calcul. Les équations concernant le changement net peuvent être intégrées aux procédures actuelles pour évaluer les aménagements qui pourraient détruire l'habitat du poisson, conformément aux exigences de la *Loi sur les pêches*. Les étapes qualitatives existantes peuvent être exprimées sous la forme de tests quantitatifs.

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1.0 INTRODUCTION

Since the 'Policy for the Management of Fish Habitat' (DFO 1986) was released by the Department of Fisheries and Oceans (DFO), the wording and potential implications of the statements in that document for the conservation and protection of fish habitat in Canada, have stimulated considerable discussion and debate. This is particularly true for the policy's guiding principle, 'NO NET LOSS OF THE PRODUCTIVE CAPACITY OF HABITATS'. Its wording implies that a quantifiable change in the productivity of fish habitat is unacceptable. The policy document lays out a framework of objectives, programs, and procedures but offers no insight on quantification.

This report outlines a mathematical framework wherein productivity of fish habitat is computed and simple equations enable the calculation of net change. If a defensible mathematical framework can be developed, implementation of the DFO's habitat management policy will be easier. The framework is primarily focused on the assessment of human developments where they encroach on or destroy fish habitat.

The framework is developed in a series of related sections. Section 2 tackles the thorny question, 'WHAT IS PRODUCTIVE CAPACITY?'. The lack of universal agreement about the answer, or answers, to that question has sidelined discussion of other issues related to policy implementation. Only a partial answer to the question is presented but succeeding sections are developed assuming a complete answer is available. Other quantitative aspects of net change calculations can be addressed and provide useful insights. Section 3 presents a framework for calculating area-integrals of productivity, assuming that a definition of productivity has been agreed. This section examines a range of options for measuring net change of productivity, looking for one that is both consistent with the policy and realistic. Section 4 explores the implications of relaxing the stringent assumptions and definitions used to develop the framework. Section 5 provides an initial indication of how the framework could be applied in the real world of fish habitat management. Finally, Section 6 offers an overview and synthesis of the implications of the framework.

2.0 WHAT IS PRODUCTIVE CAPACITY?

2.1 Definitions

In the 1986 policy document, productive capacity is defined as **'the maximum natural capability of habitats to produce healthy fish, safe for human consumption, or to support or produce aquatic organisms upon which fish depend'**. This definition is not an operational one. To obtain a defensible, workable definition of 'productive capacity of fish habitat' we must first establish the meaning of a number of terms. While productive capacity clearly has a major aspect concerned with fish production, there are qualitative aspects which also need to be addressed. The composition of productivity has many aspects, e.g., trophic - predators versus omnivores, human intervention - natural versus artificial production, and species origin - indigenous versus exotic. Both the composition of productivity and the spatio-temporal patterns of habitat requirements specific to life-stages are important qualities of productivity. However, the process of definition should begin with reference to production and productivity.

A long-accepted definition of **production**, a rate process, is that given by Ricker (1975): "The total elaboration of new body substance (collective growth of all individuals) in a stock in a unit of time, irrespective of whether or not it survives to the end of that time." This definition normally applies to a stock of a fish species occurring in a particular aquatic ecosystem and not collectively to the assemblage of species-stocks co-occurring in an aquatic ecosystem.

The units are mass per unit time but are usually in the form of kg per year and may also be scaled per unit area, e.g., per hectare. The term 'productivity' has been used as if it was synonymous with 'production' (Winberg 1971) but has commonly been used to describe the characteristic property of a particular population, community or water body. Here, fish **'productivity'** is defined as the sum of production rates for all fish species stocks within an ecosystem. Any sum of production values measured in a particular time-frame is not necessarily the maximum value attainable in a particular ecosystem. Ecosystem may be defined as a geographic area within which all the fish species present are able to complete all stages in their population cycles. Such an ecosystem definition may be too all-encompassing for habitat management purposes, and too small in larger systems with localized stocks. Productivity might also be defined for an arbitrary area of habitat as the sum of all production accrued by all stocks during the time they spend any part of their life history in that area (e.g. for spawning, rearing, and feeding) or accrued elsewhere as a result of a strict requirement to use that area of habitat (e.g. for staging, migration, or cover). [Spawning *per se* does not directly give rise to production but does enable the future production of offspring.] Fish productivity, kg per year, is the sum of fish production for all co-occurring species-stocks in that area or ecosystem.

This approach to defining productivity is consistent with the Fisheries Act. There, fish habitat is defined as **'spawning grounds and nursery, rearing, food supply and migration area on which fish depend directly or indirectly in order to carry out their life processes'**. Thus the definition covers all phases of the life history of fish and the biotic and abiotic resources upon which they depend. When assessing alterations to fish habitat, it can be difficult to understand the importance of a particular patch of habitat when that patch only contributes to the productivity of a particular portion of the fish assemblages, perhaps in portions of a few life stages. It might be argued that such complex considerations can only be achieved if the productivity of the whole ecosystem is assessed and used as a reference point for individual development projects. Although the habitat policy clearly recognizes the need for and potential role of area habitat management plans, the onus for preparing them cannot reasonably be placed on the shoulders of proponents who want to proceed with projects affecting small portions of large ecosystems.

The production, when unexploited, of each species-stock is a function of certain combinations of the available habitat features. Since the production of any species-stock is not independent of the production of all other species-stocks because of predator-prey and competitive relationships, fish productivity (the sum of production values) is constrained by biotic interactions and/or by the supplies of various habitat features. The composition of that productivity is determined by the particular mix of habitat features occurring within that ecosystem or area. The maximum level will vary from place to place, from ecosystem to ecosystem, as a result of the particular configurations of habitat arising from the geomorphological and ecological history and evolution of those places.

The summation of stock production rates can be compared with the production integral across a size-range of organisms on the production-biomass size-spectrum (Boudreau and Dickie 1989, Minns *et al.* 1987; Borgmann 1987). Since nearly all biological productivity is ultimately derived from photosynthetic activity which depends on the areal interception of sunlight energy, area is the logical spatial basis for assessing biotic productivity. Factors such as nutrient supply, physical disturbance, temperature, self-shading, etc., affect the efficiency with which sunlight energy is used to produce new biomass. Linear, e.g. edge, volumetric, and temporal aspects of habitat may be important secondary determinants of the level and composition of productivity but area provides a common basis for comparison and assessment.

Using the definitions given in the preceding paragraphs, productive capacity may be defined as the maximum potential natural productivity as determined by both the composition and diversity of fish species and other biota present in the ecosystem, and the array and supply of habitat features determine the capacity of a particular ecosystem or habitat area to produce and maintain fish biomass. The 'natural' component of the wording may then be taken to represent all the qualitative aspects of productive capacity. Given the 'natural' proviso, it makes sense to equate this maximum natural productivity with that attained originally without the interference of humans. Natural productivity of fish is defined as that achieved without significant human interference or intervention by the indigenous fish community present in an ecosystem. Further, this approach to defining productive capacity assumes that species and ecosystems evolved over long time periods, maximizing key attributes such as species richness, biomass, and productivity, and that nature is more effective than any human intervention in achieving these maxima.

The view of 'natural' used here represents a particular approach to conservation and sustainability. Olver *et al.* (1995 in press) presented an overview of conservation perspectives and argued for the adoption of an approach based on the preservation of intrinsically essential ecosystem functions and structures, an approach where human use or exploitation, wise or otherwise, is, of necessity, a secondary consideration. This is an approach stemming from the writings and philosophy of Aldo Leopold.

The interpretation and implications of the defining productive capacity as 'maximum natural productivity' are complex. Species composition of productivity and the population attributes of species contributing to total productivity can vary considerably. Biogeographic history, evolution, and locally varying supplies of habitat types and ecosystem productivities influence the composition and abundance of 'natural' fish assemblages. Habitat modifications, exploitation, and species introductions and invasions, produce changes in the qualitative and quantitative attributes, thereby decreasing natural productivity. The 'natural' qualities of fish assemblages are a result of the pristine, unperturbed, original state of their ecosystems and habitats. How to measure these qualitative features is not immediately obvious but quality of productivity must be addressed if the habitat policy is to be useful both from an ecosystem and human use perspective.

Assume there are agreed ways of measuring the production of all fish species in an ecosystem. The inclusion of qualitative considerations in the calculation of natural productivity will require that differential weights be applied to the contributing production values based on qualitative criteria determined by reference to natural conditions. For example, the production values of exotic species populations might be excluded in an estimate of natural productivity or the contribution of top predators might be weighed more while that of omnivores and herbivores might be weighed less based on an appreciation of the importance of top-down trophic regulation of energy flow in aquatic ecosystems.

Some simple examples will show the issues involved. Imagine a freshwater bay which originally had natural productivity dominated by centrarchids and esocids. If development has increased the biological productivity of the bay, perhaps through eutrophication increasing secondary production, and changed the species mix such that invaders and introductions like alewives (*Alosa pseudoharengus*) and common carp (*Cyprinus carpio*) dominate, we cannot treat current fish productivity as being equivalent to the maximum natural original productivity, or productive capacity. The production of exotics is discounted or excluded in the assessment of natural productivity. As another example, imagine a coldwater stream supporting salmonids. Watershed development alters the tree cover and groundwater such that the nutrient load to the stream increases and the water temperature rises. The fish community has, perhaps, an increased total productivity but the composition has fewer salmonids and more warmwater species such as centrarchids and ictalurids. Thus the species structure and composition of the productivity is as important as the total productivity. The unnatural productivity of altered ecosystems is discounted relative to the natural productivity of undisturbed ecosystems.

In both examples, the natural productivity of the ecosystems has been reduced. Composition is an important indicator of the natural qualities of the productivity and the original composition an important guide, accepting that, via evolution, nature has been most successful at developing species which are both able to shape their habitats and best suited to the available habitats. Generally a larger number of species is indicative of a greater level of productive capacity; a wider variety of fishes with discrete niches are better able to exploit the inherent potential of the habitat. Stressed or perturbed ecosystems lack the resilience and integration of natural ones. Sustainability is usually associated with lower levels of stress and disturbance.

Thus indices of productivity must have a qualitative component if the 'natural' aspect of the policy statement is to be adequately addressed. This can be achieved in, at least, two ways: (i) through the use of numerical qualifiers based on composition or biodiversity, or, perhaps, (ii) through the disaggregation of productivity into ecologically defined components with differential weights in the assessment of change.

2.2 Rewording the guiding principle

In the policy, productive capacity is stated to be immutable; modification of productivity does not alter productive capacity, a potential. If productive capacity is defined as the maximum natural productivity of an area, the wording of the guiding principle renders it logically inoperable and in need of modification since any areal loss and/or productivity alteration cannot be allowed by definition. The guiding principle might perhaps be better reworded as follows:

'NO NET LOSS OF THE NATURAL PRODUCTIVITY OF FISH HABITATS'.

Using this approach, productive capacity retains an important place in the policy as the maximum potential natural productivity.

2.3 Measures, indices and surrogates of productivity

Three alternatives for measuring or predicting total fish productivity exist:

1) Measurement of productivity (the sum of production for all members of the fish assemblage).

2) Measurement of indices of productivity (biomass, CPUE, presence-absence, sport or commercial yield, etc., of the fish assemblage).

3) Measurement of habitat variables which are surrogates of productivity (prior studies establish the relationship between habitat features and productivity).

These three approaches represent a graded series going from observation to prediction, from measurement to inference. In all three approaches, scientific methodology is applied insofar as measurement systems are standardized and sampling requirements are met. For operational, day-to-day management of fish habitat, the third option is preferable although for classes of development types and fish habitats reference information and knowledge obtained using the first two approaches are pre-requisites. Ecosystem management should proceed with the application of existing science and should not completely depend on the continual accumulation of new site- or development- specific science.

In the first approach, productivity is directly estimated for the pre-development situation. This approach is expensive to implement and can only be justified where (i) the value and/or size of the fishery resource is very great and (ii) there are critical unknowns or uncertainties. The post-development productivity cannot be directly estimated unless the development is undertaken on a conditional basis. If the estimates show an unacceptable loss of productivity, the development would have to be reversed. Alternately, experimental studies would be needed to allow the effects of such development to be predicted. The funds available for a proposed development would have to be large to absorb the cost of the direct productivity estimates and the experimentation needed to assess change.. Routine decision-making at the project level should require that new studies be performed in every instance.

The second approach draws on existing data or new data which can be readily obtained from limited surveys. This approach can still be quite expensive and may be used in a hasty, incomplete manner because of time and financial constraint; the proponents of development project want quick answers. A development project which produces permanent year-round alterations of fish habitat cannot be adequately assessed via severely time- spatially- and financially- constrained surveys. Besides, the effective use of index-type fish information still depends on the availability of predictive models developed with the first approach to guide its interpretation and application. There may be a strong temptation to rely on incomplete and poorly understood data, ignoring the pre-existing wider body of conceptual understanding.

The third approach uses models wherein productivity is predicted using a variety of habitat variables (depth, substrate, nutrients, temperature, etc.). This approach has the greatest potential to provide cost-effective and timely methods of estimating net change of natural productivity, if there is a willingness to under-write the initial development of predictive models. This approach can be applied using habitat measurements obtained in the field and from maps. Previously synthesized knowledge can be used to specify which fish species need to be considered based on zoogeographic and ecological niche considerations. The areas and features of habitat are specified for the current time and after the project. The predictive models are then used to predict productivities and net change due to development.

The procedures for measuring production, and hence total productivity, are well developed while methods for assessing the qualitative aspects are still rudimentary. However, Karr (1981), Fausch *et al.* (1990), Minns *et al.* (1994), and others have begun to develop qualitative compositional indices reflecting trophic and diversity. Where many stocks or strains are involved as with salmonids, genetic compositional weights will be required.

For the purposes of succeeding sections in this report, I have assumed that natural productivity is completely defined and measurable. This is not to ignore or understate the difficulties involved. However, as will be shown, there are aspects of the quantification of net change which do not depend on how productive capacity and productivity are defined.

3.0 CALCULATING NET CHANGE OF PRODUCTIVITY

Fish productivity is an areal integral, the numerical product of the area of a patch of fish habitat and its unit-area fish productivity. This approach was adopted in the U.S. Fish and Wildlife HEP procedures (Terrell 1982; USFWS 1981). Changes to both the area and the unit-area productivity rate must be considered in the development of a numerical basis for assessing the net change of the natural productivity of fish habitats.

The basic concepts are initially developed using a simplified framework which assumes homogeneity of habitats and a single reference unit-level of maximum natural fish productivity, or productive capacity (P_{MAX}), equal to the original, pre-disturbance productivity. [A list of area and productivity variables is given in Table 1.] Here, productivity is assumed to represent both its qualitative and qualitative aspects, i.e. natural productivity.

3.1 A framework for quantifying fish productivity

Consider an area of habitat (A_O) sufficiently large to encompass proposed habitat losses and alterations and possible mitigation, compensation, and restoration actions, i.e., all effects of the alteration will occur within A_O (Figure 1A) attributable to a single new project. This is the original habitat where productivity equals productive capacity. Assume that all parts of the area had the same maximum unit-area productivity (P_{MAX}) and that previous habitat alterations have uniformly reduced the natural productivity to the current level, P_T. Previous alterations may also have caused some elements to disappear completely (e.g. through in-filling, drainage of wetlands, etc.). The area lost is A_E (E for eliminated or extinct) leaving the current supply at A_T:

$$A_O = A_T + A_E \tag{3.1}$$

This situation is represented in Figure 1B.

Given these basic assumptions, maximum, original productivity (productive capacity) can be calculated:

Maximum productivity = Productive capacity

$$= P_{MAX}.A_O = PC \quad (3.2)$$

This quantity can be visualized by plotting a graph of unit-area productivity versus area (Figure 2); maximum productivity is the shaded area enclosed by the defined levels of P and A relative to the origin of the axes (0,0). Maximum natural productivity or productive capacity (*PC*) provides the overall reference point for all other productivity levels.

Now consider the current situation where both area has been lost (A_E) and unit-area productivity is P_T ($< P_{MAX}$). This is the situation that must be confronted in most ecosystems as the habitat policy was developed long after most ecosystems had sustained areal losses and damage to productivity. Total productivity may often have increased in degraded ecosystems due to increased nutrients and temperatures, implying that P_T could be greater than P_{MAX}. However, total productivity is not natural productivity in the current situation and does not include the qualitative components of natural productivity which are usually degraded as a result of development. Current productivity is calculated as follows:

$$\text{Current productivity} = P_T.A_T = CP \quad (3.3)$$

This can be represented via the cross-product as the shaded area in Figure 3; the maximum, original productivity is shown for comparison. The isoline shows all feasible combinations of area and unit-area productivity matching current productivity (Figure 3). At this point, a change of productivity from maximum to current can be calculated:

Net change = Productive Capacity - Current Productivity

$$NC_x = PC - CP$$

$$= P_{MAX}.A_0 - P_T.A_T \quad (3.4)$$

This can be re-arranged by substitution using 3.1 to isolate the area eliminated:

$$= \quad P_{MAX}.A_E + [P_{MAX}-P_T].A_T \qquad (3.5)$$

This equation provides the starting point for calculating further net change relative to any new human development project.

Next, consider a new habitat alteration which affects part of A_T. This alteration can cause a further loss of habitat(A_L), and the productivity of a further area (A_M) to be modified (P_M), leaving an area unaffected, A_U (Figure 4A):

$$A_T \quad = \quad A_L \quad + \quad A_M \quad + \quad A_U \qquad (3.6)$$

After the project is completed, we can again compute the productivity of the area:

$$\text{Prod. after project (T+1)} \quad = \quad P_{T+1}.A_{T+1} \quad = \quad PP \qquad (3.7)$$

Since $A_{T+1} = A_M + A_U$ and unit productivity is unchanged in A_U, the equation for PP can be restated as follows:

$$PP \quad = \quad P_M.A_M + P_T.A_U \qquad (3.8)$$

$$\text{Where} \quad P_{T+1} \quad = \quad [P_M.A_M + P_T.A_U]/[A_M + A_U]$$

$$A_{T+1} \quad = \quad A_M + A_U$$

This change can be considered in two ways depending on whether or not any area is loss ($A_L >$ 0 or $A_L = 0$). Since under the DFO policy any new project must result in an increase of integral productivity, the areas defined by the intersection of area and unit productivity values must lie, at least, above the current productivity isoline (Figure 3). The two cases are shown in Figure 5. It is easier to achieve a productivity gain if no loss of area is involved. These productivity increases have yet to be assessed for net gain.

3.2 Analysis of options

Equations 3.1-3.8 and figures 1-5 describe the areas and integral productivities at various points in time. Net change of fish productivity can be calculated in a number of ways, depending on the assignment of responsibility for past and proposed changes in area and productivity. The current productivity isoline (Figures 3 and 5) does not account for the permanent loss of productivity associated with areal losses of fish habitat.

Reference points for calculation of net change must be selected. There are three obvious choices with varying degrees of stringency:

(i) maximum, original productivity (P_{MAX}) which is the most stringent option;

(ii) current productivity (P_T) which is the least stringent option and effectively ignores productive capacity (maximum, original productivity); and

(iii) a combination where P_{MAX} is used for losses and P_T for modifications;

Another possibility involving use of P_{MAX} for modifications and P_T for losses was nonsensical and was not considered. Each of the three options is examined, with consideration of the implications and disadvantages.

3.2.1 Option A - P_{MAX} is reference for loss and modification:

This is the approach implied by the existing guiding principle, *no net loss of productive capacity*. In the net change equation, the productivity in the portion of the area A_T which is unaltered, A_U, does not change and, hence, is excluded for further consideration:

$$\text{Net change (T to T+1)} = NC_A$$

$$= [P_M - P_{MAX}].A_M - P_{MAX}.A_L \qquad (3.9)$$

In this scheme, the proponent is accountable for all losses and can do nothing to offset losses because the reference point is P_{MAX}, productive capacity, for both modifications and losses. By definition, P_M is less than or equal to P_{MAX} and, hence, there will always be a net loss regardless of the possible loss of habitat area. Strict adherence to this option gives human development no scope within the constraint of the guiding principle. This option is not a viable basis for policy implementation.

3.2.2 Option B - P_T is reference for loss and modification:

Here the guiding principle, indeed the whole idea of productive capacity, is ignored and current productivity (P_T) is used as the reference point for all changes:

$$NC_B = [P_M - P_T].A_M - P_T.A_L \tag{3.10}$$

In this scheme, the proponent is only held accountable for losses relative to the current situation and can easily offset losses. The implications can be expressed graphically (Figure 6). After assuming the net change equals zero, equation 3.10 can be rearranged:

$$A_L/A_M < P_M/P_T - 1 \tag{3.11}$$

If P_M is greater than P_T, the proponent can produce an apparent net gain. Since P_T could be quite low relative to P_{MAX}, this scheme does nothing to offset the productive capacity lost in area A_L. This scheme is inconsistent with the intent of the guiding principle and therefore must be rejected as a viable option for policy implementation. This option was the basis for current isoline shown in Figure 3. Assuming all losses occur at once after productivity has declined from P_{MAX} to P_T, we can calculate the maximum percentage losses of habitat which can be permitted under option B if P_M equals P_{MAX}, maximum percent allowable loss = 100*(1 - P_T). Thus, the allowable loss is greater, the more current unit-productivity has been degraded from the original maximum level; past damage is rewarded by greater destruction allowances. This option achieves the antithesis of the policy objectives by completely ignoring productive capacity.

Option B is sometimes mistakenly used currently. This is probably due to misinterpretation or ignorance of the terms of the habitat policy. Since the original, maximum productivity of a habitat may be difficult to imagine or remember where significance alteration has occurred, there may be a tendency to adopt the current productivity as a substitute.

3.2.3 Option C - P_{MAX} is reference for loss and P_T for modification:

In option C, the proponent is held accountable for permanent losses of productive capacity on the grounds that productive capacity can no longer be restored by any means if the habitat itself is eliminated. However, the proponent is only held accountable for changes relative to current productivity in those areas where productivity is modified by development on the grounds that the modification does not preclude the future possibility that productive capacity might be achieved by additional modifications.

$$NC_C = [P_M - P_T].A_M - P_{MAX}.A_L \qquad (3.12)$$

This equation is the current equivalent of equation 3.5. The net change equation can be rearranged to compare loss/modification ratios with productivity differences when net change is greater than zero:

$$A_L/A_M < [P_M - P_T]/P_{MAX} \qquad (3.13)$$

$$\text{or} \quad < \quad P_M - P_T$$

if P_{MAX} as the maximum possible value takes a reference value of 1. The ratio lines are parallel (Figure 7) rather than radiating from the origin as occurred with option B; the area ratio is determined by productivity difference rather than by their ratio. Here it is possible to offset losses because the reference point is P_T for modifications. To meet the net gain requirement, P_M must be greater than P_T and, after allowance for area, the gain in the modified area must exceed the productivity loss in A_L. Option C represents a compromise approach and is consistent with the intent of the original and proposed, revised guiding principles while allowing some human development. Option C is the only option which provides some protection of productive capacity while allowing some human development which encroaches on fish habitat to proceed. Hence option C is the recommended basis for assessment net change of natural productivity of fish habitats.

Option C appears to be the best compromise available for implementing quantitative assessment of net change. Using option C as the basis for measuring net change of productivity has a number of consequences:

1. If P_M is less than or equal to P_T then a net loss of productivity is unavoidable without compensation elsewhere. Since a net gain is required under the policy, P_M must always exceed P_T in any development

2. If $[P_M-P_T].A_M$ exceeds $P_{MAX}.A_L$, a net gain of productivity occurs.

Using the isoline approach used in Figures 3 and 5, it is possible to compute an isoline of productivity which reflects the implication of option C (Figure 8); any development must result in an endpoint lying above the isoline for net gain to occur. The productivity isoline based on option C (Figure 8) shows that large increases in unit productivity are needed to offset the negative effects of any habitat loss. The P_{MAX} loss isoline is much shallower than the P_T loss (current) isoline.

In pristine, undisturbed habitats, current productivity will closely approximate original, maximum natural productivity. In these circumstances, options A and C have similar properties. Less loss or degradation will be allowable. This outcome is consistent with the intent of the habitat policy, which is to prevent loss in pristine or relatively undeveloped habitats and to reverse past perturbations in developed habitats.

3.3 Extensions to the framework based on option C

Now other features of the policy statement can be added which have bearing on estimation of net change of productivity: Mitigation, Compensation, Restoration, Enhancement. Mitigation involves amendments to proposed development which will minimize losses, offset unavoidable losses, and increase the productivity contribution ($> P_M$) of the modified area (A_M). Mitigation seeks to minimize A_L and ensure that P_M at least equals P_T. If $A_L > 0$ then $[P_M-P_T]/P_{MAX}$ must be $> A_L/A_M$; the percentage productivity increase relative to maximum productivity must be greater than area lost as a percentage of area modified. Mitigation involves minimizing A_L and A_M and maximizing P_M. If mitigation is not possible, compensation may be considered to offset the unavoidable losses. Compensation involves choosing another area within A_U and increasing its productivity to P_C such that the net gain in A_C offsets projected losses in A_L and A_M:

$$NC_{C'} = \text{modification} + \text{compensation} - \text{loss}$$

$$= [P_M-P_T].A_M + [P_C-P_T].A_C - P_{MAX}.A_L \qquad (3.14)$$

Compensation in the form of stocking or other artificial rearing practices does not fit the definitions as the 'natural' property in an essential element of the DFO policy. Restoration involves increasing natural productivity from P_T towards P_{MAX} and, where possible, recovering part of the eliminated area (A_E). Enhancement must be planned carefully as it aims to raise productivity beyond the pre-existing productive capacity and usually involves qualitative changes to productivity, favouring some fish stocks over others. Degradation and enhancement can easily become two sides of the same coin and the difference depends on one's philosophical, ethical perspective on nature and ecosystem integrity.

The identification of A_L is usually easy while A_M can be difficult as it has two components, direct and indirect. The modified-direct, A_{MD}, is the habitat altered by the project, e.g. the bottom depth is changed from 1 m to 2 m, the mud substrate is replaced by sand, etc., via the direct human intervention. The modified-indirect, A_{MI}, is the habitat altered as the ecosystem responds to the direct alteration, e.g., modified fetch causes altered sedimentation and plant growth. A_{MD} can be determined fairly easily by inspection but A_{MI} will involve an analysis and knowledge of the interactions between ecosystem responses to direct alterations and losses and the behaviour of the fishery resources affected. For example, in a marina development, breakwall construction and contour alterations represent modified-direct effects while the sheltering affect of the breakwall produces modified-indirect effects over area that goes beyond the direct construction effects.

3.4 Implicit development limits

Besides assessing projects one by one, we need to examine how upper bounds on development, limits to cumulative change as required under the Canadian Environmental Assessment Act proclaimed early in 1995, can be set. Elsewhere, Minns(1995 *in press*) has argued that an upper limit, a maximum allowable change (MAC), on ecosystem alterations might be 50 percent, whereby a limit is set on all natural features of an ecosystem. Because of the inherent connectedness of ecosystems and non-linearity of responses, it is likely that a 50 percent limit on one feature will require a more stringent limitations on another features (< 50 percent). Of course, this present approach to net change may not appear to solve the problem of how to set limits on development but, in fact, the net change equation (3.12) contains implicit development limits.

To compute the minimum percentage (C_T) of A_T to be conserved to protect the equivalent of the current productivity of the area remaining. Substituting $C_T.A_T$ for A_M and $(1 - C_T).A_T$ for A_L in 3.12 and rearranging:

$$C_T \text{ must be} > P_{MAX}/[P_{MAX} + P_M - P_T] \quad (3.15)$$

Prior losses (A_E) are neglected and would only be considered in a restoration project. The minimum conservation requirement is 50 percent which is obtained when the difference between P_M and P_T maximal, i.e., when $P_M = P_{MAX}$ and $P_T = 0$. When $P_M = P_T$, 100 percent must be conserved. In most realistic situations, P_M will be less than P_{MAX} and P_T will be greater than zero. For example, if $P_M = 0.8$ and $P_T = 0.2$, then $C_T = 62.5$ percent. The results requires that C_T be higher in fish habitats where degradation, reductions of natural productivity, has been least; near-pristine habitats will be subject to more stringent development limits than highly degraded one. If relative P_{MAX} and P_T values can be established for a fish habitat, a conservation target can be set. Of course, the limit setting cannot be repeated iteratively. The reference 'current' situation must be based on the state of fish habitat when the DFO fish habitat policy was promulgated.

4.0 RELAXING INITIAL ASSUMPTIONS

There are many unspecified aspects of the net change framework which might appear restrictive or to limit its scope for application: 1) Habitat does not consist of large homogeneous areas with a fixed unit rate of productivity, 2) Both areas and unit-rate productivities will have uncertain values, 3) Rareness of habitat types critical for life-history closure, 4) Transient effects, and 5) Non-indigenous species.

4.1 Adding heterogeneity

Fixed values of P do not have to apply across the whole of A_O. As long as the spatial patterns of P (with any subscript) can be described, the area integrals can be computed and the equations applied. If an area is divided into a mosaic of homogeneous units, each with characteristic values for unit-productivities, the net change equation can be generalized,

$$NC_C = \Sigma[P_{Mi}-P_{Ti}].A_{Mi} - \Sigma P_{MAXi}.A_{Li} \qquad (4.1)$$

where i is the index of the sub-areas.

4.2 Statistical uncertainty

Both areas and unit-rate productivities will be subject to uncertainty. As the means, variances,and covariance of A and P can be specified, the mean and variance of integral productivities can also be calculated. Confidence intervals could be added to the productivity-area diagrams.

The variances and covariance will determine the levels of precision required to be able to show that a net change occurs. Traditionally, statistical criteria determine significance and can impose overly-stringent requirements. Detecting a significant net gain or loss may be extremely difficult. Where net loss is possible, decision-making will need to be conservative. The precautionary principle, which is increasingly being adopted as a philosophical basis for conservation and protection of natural ecosystems, can be used (Minns 1995 *in press*). The onus of proof shifts to the proponent. The proponent must prove the habitat alteration will not cause a net loss and the regulatory agency assumes that an net loss will occur as a default.

4.3 Rareness and population dynamics effects

The impact of accelerating the disappearance of already rare habitat types may exacerbate the impacts on productivity if those habitat types have a critical role in the population dynamics of the fish species and assemblages involved. Clearly with rareness, there is a need to have a way of ensuring that important habitat feature, 'critical habitats', acquire increasing values as they become rarer. Minns *et al.* (1993) defined 'uniqueness', or rarity, as the complement of the areal proportion represented in the total ecosystem (one minus percent occurrence); as a habitat type becomes rarer, so its uniqueness increased to a limit of one at extinction. Uniqueness weights can be applied to all habitat types, thereby emphasizing the greater contribution of certain types to productivity. Such an approach would be difficult to apply on a case by case basis for development projects in the absence of an overall ecosystem assessment. This, of course, only re-emphasizes the important role of area habitat management plans in implementation of the habitat policy.

Detecting the relative contributions of different habitat units to overall productivity and ascribing criticality to a small sub-area is difficult but not impossible. In a population of fish, a small area may provide for the spawning needs while a larger area provides for adult feeding habitat. Proportional reductions in either area might be expected to have similar consequences although on an absolute basis unit losses of spawning habitat will have more impact. The actual response depends on which life stage's habitat requirements are limiting the population. Adding population dynamics and life-stage closure to the assessment process further complicates matters.

When net change calculations are performed using a mosaic of habitat sub-units, no sub-unit is likely to be able to produce a self-sustaining population or fish assemblage by itself. Hence unit-rate productivities need to be expressed in terms of their contribution to life-stage and population-cycle completion. Deletion or severe depletion of a particular step can cause loss of or drastically reduced productivity.

4.4 Transient effects

At present, the framework has been developed for situations where changes in areas and unit-productivities are permanent. In many development projects, transient constructions effects can be far more important than the permanent effects once the project is completed. Adding transience to the framework will require that a time dimension be added to the scheme wherein the timing and duration of development activities and life stage activities of fish are explicitly considered. One approach to this might involve the use of techniques developed to assess the population viability of rare and endangered species, where transient activities are judged in relation to extinction probabilities (cf Soulé 1987). This approach automatically expands the spatial context to one encompassing all life stage requirements of the population and potentially of adjacent populations where recolonization might play a role.

4.5 Non-indigenous fish species

In many places, non-indigenous fish species stocks have been established by introduction or by invasion. Where the presence of these fish species has produced substantial changes in assemblage composition, establishing the reference points for net change calculation will be more complicated. Invasions or introductions of other non-fish species might also have altered the forms and distribution of ecosystem productivity available for fish. Of course, there is a possibility that the current state of the fish assemblage's productivity may be a joint function of habitat changes, exploitation, and introduced species and producing net gains of productivity might promote the re-establishment of productivity similar in form, if not level, of the original ecosystem Restoration activities might reduce the contribution of exotic species to total productivity by preferentially promoting the success of native stocks.

5.0 RELATIONSHIP TO ENFORCEMENT OF THE FISHERIES ACT

To be useful, the net change framework must mesh with the established process by which applications for approvals to alter fish habitat are evaluated. In this framework, a net loss of productivity would be considered a 'harmful alteration of fish habitat' and a series of steps can be envisaged:

Step 1: Will the project as proposed achieve a net gain?
If YES then go to Step 6 else if NO then go to Step 2.

Step 2: Will the project with mitigation achieve a net gain?
If YES then go to Step 6 else if NO then go to Step 3.

Step 3: Has the defined loss limit or threshold been exceeded?
If YES then go to Step 5 else if NO then go to Step 4.

Step 4: Will compensation produce a net gain?
If YES then go to Step 6 else if NO then go to Step 5.

Step 5: Net gain is not feasible and the project does not proceed.

Step 6: Net gain is achieved and the project proceeds.

In Step 1, the net change calculation is performed using the values of A_M and P_M provided in the initial proposal:

$$[P_M - .P_T].A_M - P_{MAX}.A_L > 0 \qquad (5.1)$$

For net gain to occur in equation 5.1, the increase of productivity in the modified area must exceed the productive capacity of the area which will be lost. Then in Step 2, mitigation actions are put forward which result in new values of A_L, A_M, and P_M being developed. Equations 5.1 is recomputed. In Step 3, the potential exceedance of any development limit or threshold for the target ecosystem is examined using equation 3.15. The development limits, expressed as a conservation requirement, were locked in when the habitat policy came into force. If the limit has not been exceeded, Step 4 is computed. Compensation is allowed in another area of habitat:

$$[P_M - P_T].A_M + [P_C - P_T].A_C - P_{MAX}.A_L > 0 \quad (5.2)$$

The increase of productivity in the compensation area is added. If net gain is unattainable via these various steps, the project should not proceed. Otherwise, if a net gain is attained via one of the previous steps, there should be no obstacle to allowing the project. An authorization is required if A_L is greater than zero since a permanent loss of productive capacity occurs.

The implications of the steps outlined above can be examined in a simple example. Consider the construction of a marina on the open shoreline of a large lake. Such a development often involves the modification of the shoreline and construction of a breakwall projecting into the lake to provide a wave shelter for boats and infrastructure. Construction of the breakwall and along the shoreline produces habitat loss (A_L). Adjacent to those new structures, habitats will have been directly modified with new contours and substrates (A_{MD}). Then in the vicinity of the marina and potentially up- and down-drift of the site, patterns of thermal habitat, vegetation, sedimentation and erosion will produce an indirectly modified area (A_{MI}). On the deeper Great Lakes, the construction of the marina is often accompanied by increases in warmwater fish assemblages which replace cool- and coldwater ones that occupied the undeveloped, exposed littoral area. Overall productivity may be greater but the qualities (composition and diversity) of the new productivity will be different from the maximum, original productivity, requiring the new productivity to be discounted. Of course, new substrates on the outer edge of the marina may increase the habitat supply for selected coldwater forms. The exact weighting will depend on the fish community objectives of the agencies stewarding the natural fish resources.

6.0 DISCUSSION

The analysis of the different approaches to measuring net change did lead to the identification of a workable option (C) which represents a compromise between the extremes of laxness and stringency. This proposed approach to quantifying net change will require a wider debate but should provide the groundwork for a consistent reproducible assessment of net change which fulfils the promise of the original policy document (DFO 1986).

The algebraic and graphical approach taken here to computing net change of productivity allows the process of assessing development to be decomposed into a series of steps. The primary separation of habitat areas from unit productivity vales means that a large part of the assessment can be completed without the need to agree on measures of productivity. Estimating the size of affected habitat areas is relatively straight-forward. The analyses presented here used proportional indices of productivity. In many assessment situations, it is the relativity of unit productivity vales which will decide if a net gain or loss will occurs. In extreme cases, productivity differences will be obvious and, hence, fixing on exact values will not alter the results. Where the results hinge on minor differences between productivity values, it is more likely mitigative and compensatory actions will be available. For example, a proponent may wish to destroy a large portion of a fish habitat. If no compensation or mitigation is possible, the most generous assumptions of unit productivity values can provide a preliminary determination. If no achievable productivity increase in the remaining area can match the productivity of the area lost, the development can not be approved and it is not necessary to obtain exact productivity values.

The definition of productive capacity is still incomplete, insofar that an agreed framework for expressing the qualitative aspects has yet to be completed. However, the quantitative framework demonstrates that net change can be calculated given agreed values of P. The equations show there are numerical constraints when habitat loss occurs. Thus it should be easy to identify destructive projects where no relative improvements in modified areas can offset absolute losses. The equations also embody implicit conservation rules which can aid policy implementation. Future work will involve demonstrations of the utility of this quantitative approach and the development of agreed methods of specifying the qualitative components of productivity.

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Table 1 Area-integral, area, and productivity rate coefficients used in the calculation framework for measuring net change of productivity of fish habitats.

Coefficient	
	Area-integral productivity values
PC	Productive capacity, or maximum productivity
CP	Current productivity
PP	Post-project productivity
NC_A	Net change of productivity relative to maximum only
NC_B	Net change of productivity relative to current only
NC_C	Net change of productivity relative to maximum & current
	Area designations of fish habitat
A_O	Total original area of habitat
A_T	Remaining area of habitat at current time (T)
A_E	Area of habitat eliminated, extirpated, extinguished prior to time T
	$A_O = A_E + A_T$
A_L	Area lost to new project at T+1
A_M	Area modified by new project at T+1
A_{MD}	Area directly modified by new project
A_{MI}	Area indirectly modified by new project
	$A_M = A_{MD} + A_{MI}$
A_C	Area of compensation for new project at T+1
A_U	Area within A_T unaffected by new project at T+1
	Natural productivity per unit-area
P_{MAX}	Maximum, original value = **productive capacity**
P_O	Original productivity $= P_{MAX}$
P_T	Present productivity $<= P_{MAX}$
P_M	In modified area (A_M) after new project $<= P_{MAX}$
P_C	In compensation area (A_C) after new project $<= P_{MAX}$

Figure 1. The allocation of habitat area as it was originally (A) and at it is now after some habitat has been eliminated (B).

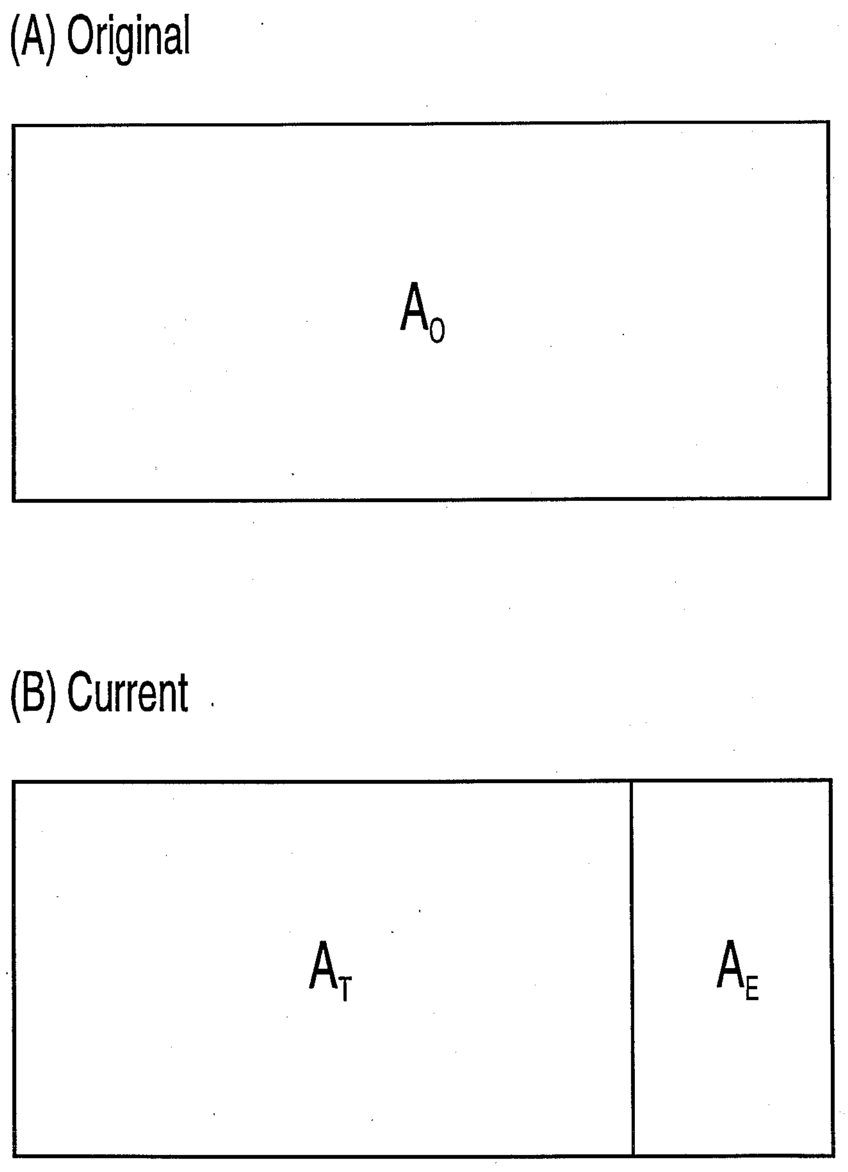


Figure 2. The relationship between unit-area productivity and area of fish habitat showing maximum natural productivity or productive capacity. The shaded area is *PC.*

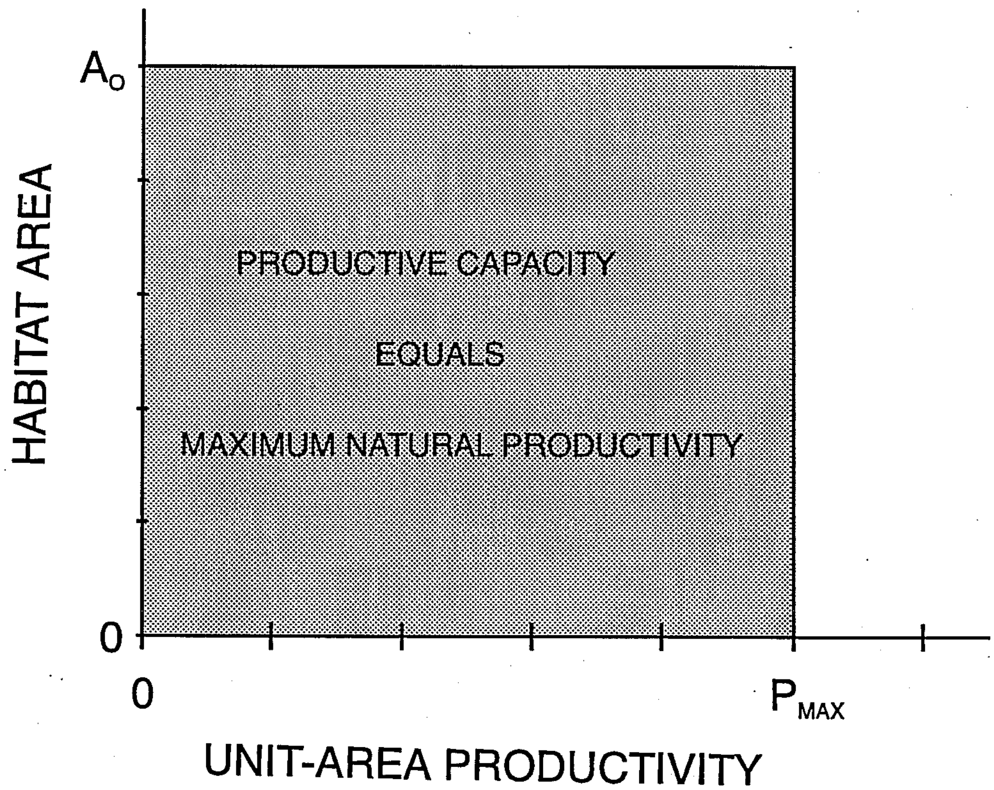


Figure 3. Current productivity (*CP*) in relation to productive capacity. The isoline shows all A.P combinations equal to *CP*.

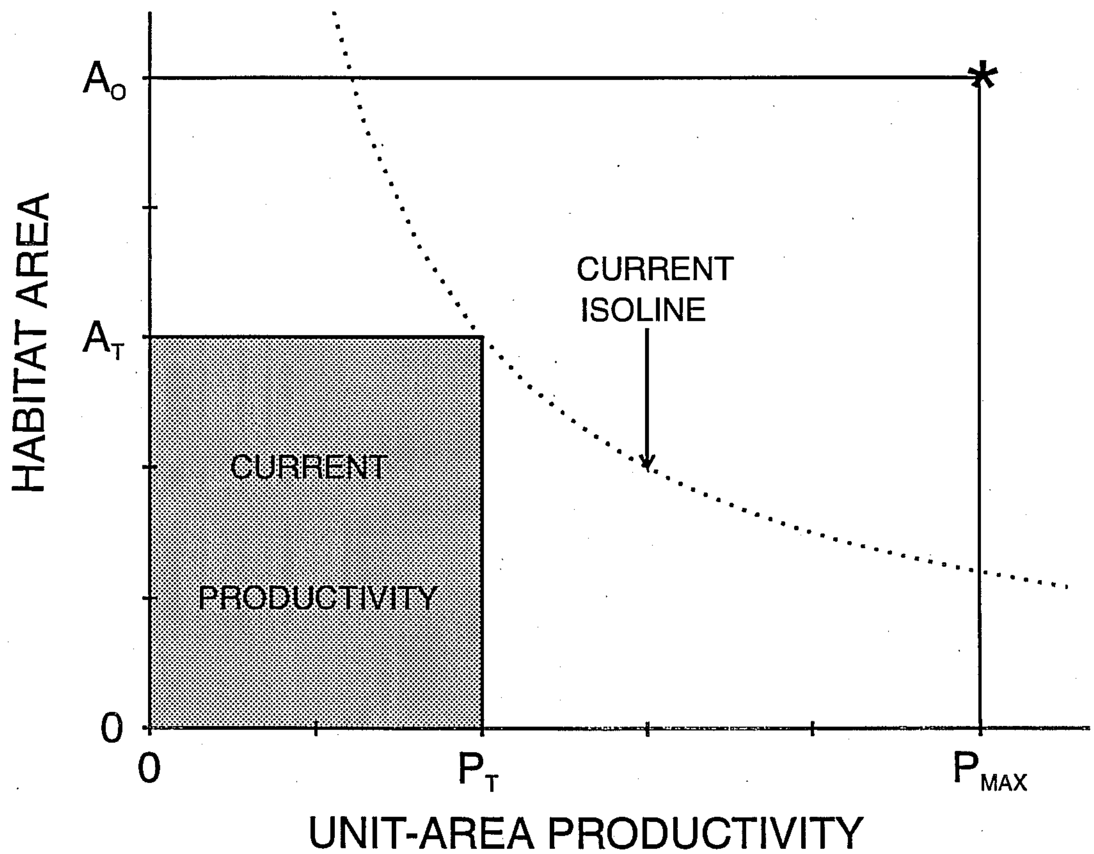
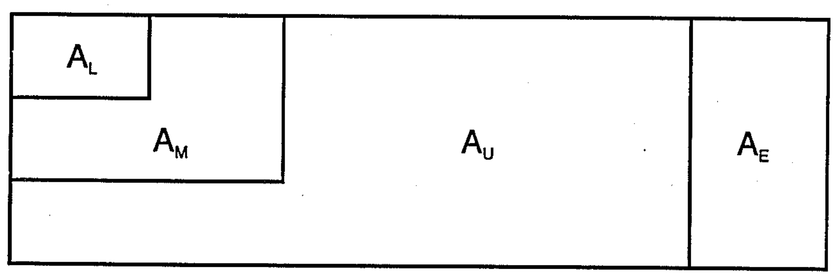


Figure 4. Allocation of areas after a project is completed, involving some loss and modification, without (A) and with (B) compensation.

A) Post-Project



B) Post-Project + Compensation

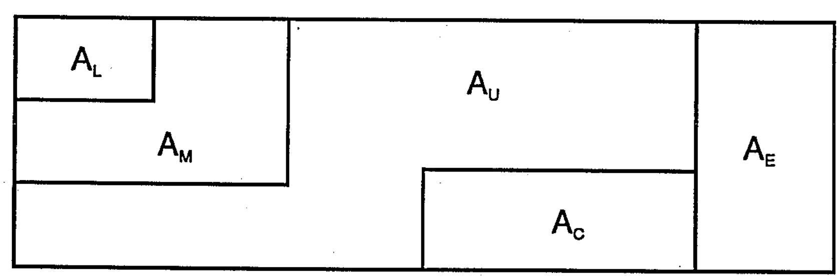


Figure 5. Change in productivity after project, with (A) and without (B) habitat loss.

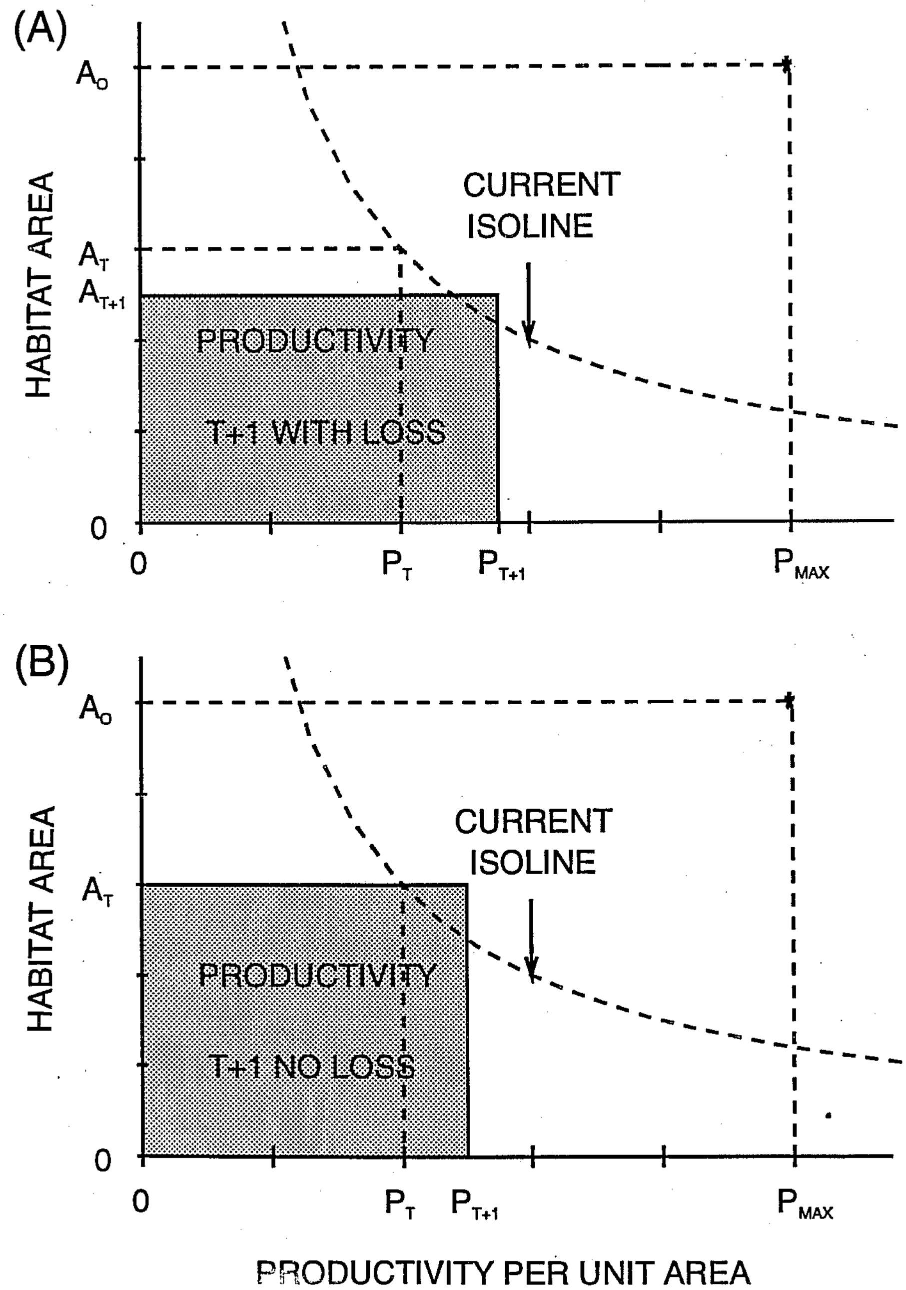


Figure 6. Option B - Combinations of current and modified unit-area productivity giving a net gain. The isolines show the ratios of loss:modified area required.

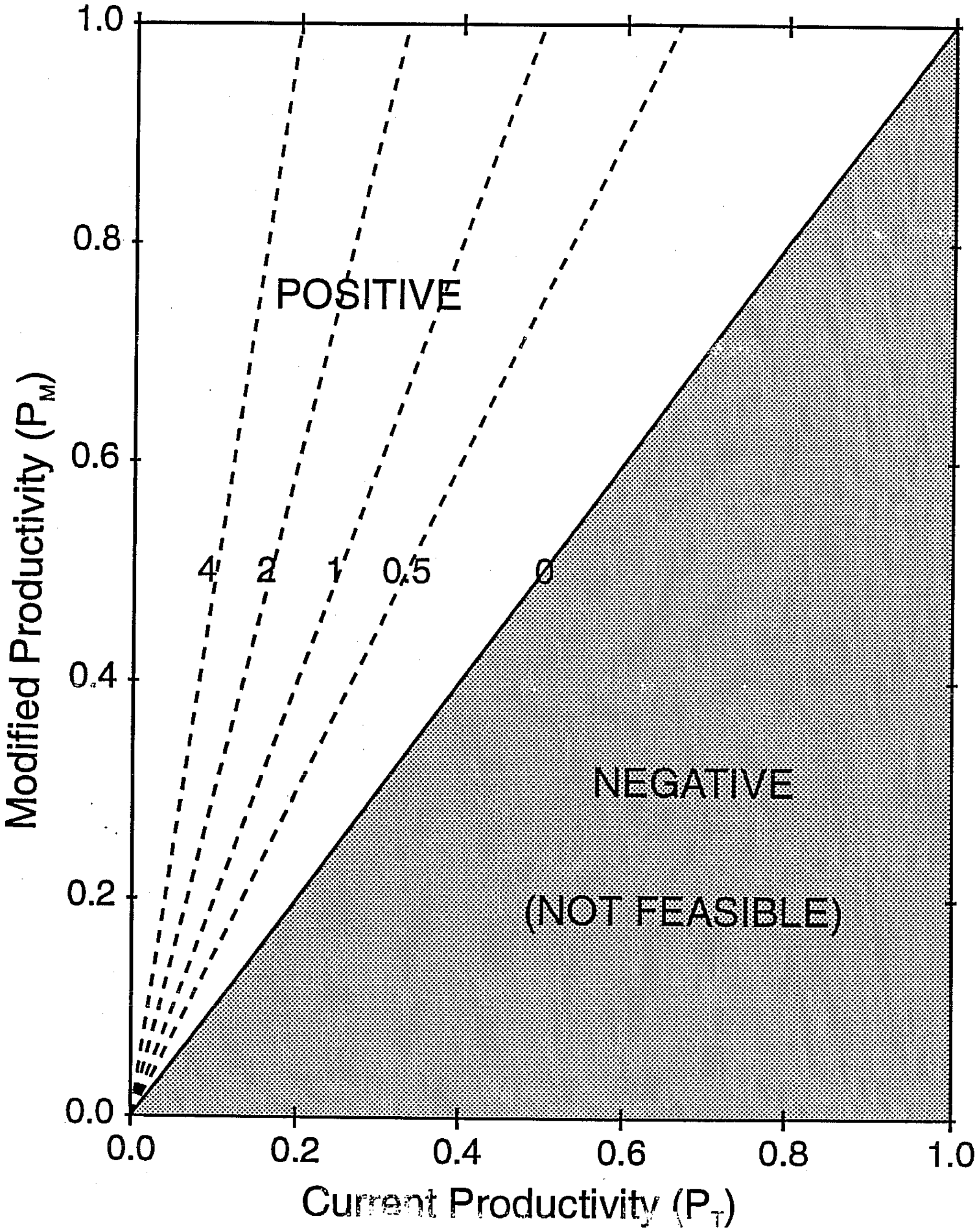


Figure 7. Option C - Combinations of current and modified unit-area productivity giving a net gain. The isolines show the ratios of loss:modified area required.

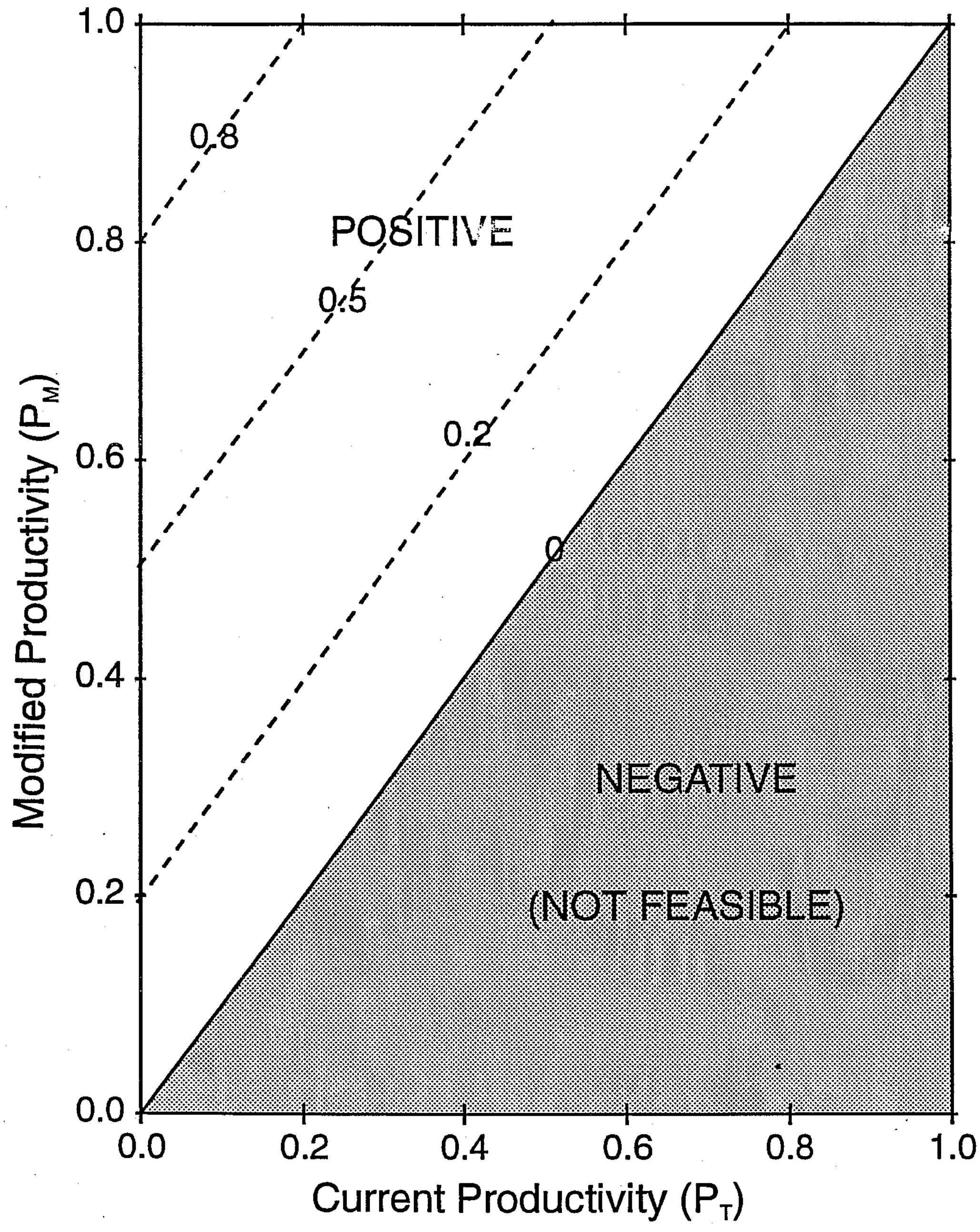


Figure 8. Comparison of net gain isolines for options B and C. Charging loss at P_{MAX} requires greater gains.