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THE CONTRIBUTION OF EXTERNAL INPUTS AND INTRINSIC STATE CONDITIONS TO AGROECOSYSTEM PRODUCTIVITY

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Key Words: Agroecosystems, C_3-C_4 Crops, Erosion, Farm Size, Harvest Index, Input Efficiency, Limiting Factors, Net Primary Production, Subsidy-Stress Curve.

ABSTRACT

Productive inputs —materials or actions— function in agroecosystems to provide resources that stimulate biological growth and storage, to maintain favorable physical conditions for growth processes, and to protect vulnerable domesticates against biotic and physical injury. These inputs, to some degree, substitute in simplified agroecosystems for the intrinsic organization —the productive conditions and reinvestment processes— which exists in natural ecosystems. Thus, the maximum efficiency of external inputs may, under simplified agroecological conditions, bear a close relationship to the dynamics of fertility and regulation in nature. Agroecosystem inputs may cause proximate or degradative stress, as well. Too much of any productive input may inhibit the immediate processes of growth and storage. Agricultural exploitation, with export of harvest, however, may also impair agroecosystem organization still further, tending to reduce potential productivity. In particular, input actions that accelerate erosion may cause long-term degradation and substantial reduction of productivity. Artificial inputs function to offset these reductions, and permit production levels approaching or exceeding natural levels. Thus, a subsidized NPP fraction can be recognized for agroecosystems. The magnitude of this fraction varies for ecosystems limited by different factors such as water, nutrients, and seasonal temperature regime. Analysis of forage and crop production levels in relation to productive input intensities suggests that C_3 crop species may approach, but not exceed, natural levels of productivity for temperate zone ecosystems, but that C_4 species may substantially exceed such levels. In farming practice, the costs of inputs come strongly into play, and these have led to a pattern of increased utilization of materials inputs, relative to labor, and an increase in the size of the most economical farm in the United States in recent decades.

Key Words: Agroecosystems, C_3 and C_4 Crops, Erosion, Farm Size, Harvest Index, Input Efficiency, Limiting Factors, Net Primary Production, Subsidy-stress Curve.

RESUMEN

Los inputs productivos —materiales o acciones— funcionan en los agroecosistemas para proveer los recursos que estimulen el crecimiento y almacenamiento biológico, para mantener las condiciones físicas favorables para los procesos de crecimiento y para proteger las especies domesticadas vulnerables contra el daño biótico o físico. Estos inputs, hasta cierto punto, sustituyen en los agroecosistemas la organización intrínseca —las condiciones productivas y los procesos de reinversión— que existen en los ecosistemas naturales. Por tanto, la máxima eficacia de los inputs externos puede, bajo condiciones de agroecosistema simplificado, estar íntimamente relacionada a la dinámica de fertilidad y regulación de la naturaleza. Los inputs en el agroecosistema pueden también causar un stress que conduce a la degradación. Un exceso de cualquier input productivo puede inhibir los procesos inmediatos de crecimiento y almacenamiento. La explotación agrícola, con exportación de cosecha, puede, de todos modos, dificultar aún más la organización del agroecosistema, tendiendo a reducir la productividad potencial. En particular, las acciones de input que aceleran la erosión pueden causar degradación a largo plazo y una reducción sustancial de la productividad. Los inputs artificiales funcionan amortiguando estas reducciones y permitiendo niveles de producción que se aproximen o excedan los niveles naturales.

Así pues, en los agroecosistemas podemos reconocer que una fracción de la PPN está favorecida. La magnitud de esta fracción varía para ecosistemas limitados por diferentes factores como agua, nutrientes y régimen estacional de temperaturas. El análisis de niveles de producción de forrajes y cultivos, en relación a las intensidades de input productivo, sugiere que especies de cultivos C_3 pueden aproximarse, pero no exceder, los niveles naturales de productividad para ecosistemas de áreas templadas, pero que las especies C_4 pueden exceder sustancialmente tales niveles. En la práctica agrícola, los costos de los inputs entran en juego de forma importante, y éstos han conducido a un modelo de utilización incrementada de inputs de materiales, con relación a la mano de obra, y a un incremento del tamaño de la granja considerada más económica, en las últimas décadas, en los Estados Unidos.

INTRODUCTION

The practice of agriculture consists of the utilization of external ecosystem inputs, either materials or actions, to stimulate the production of harvestable foods. These inputs are of four basic types. Genetic inputs consist of the crop and animal varieties that have been selected for their abilities to produce desired food products under particular conditions. Productive inputs are those, such as fertilizers, irrigation water, and augmented CO_2 levels, that are active participants in the production process. Facilitative inputs, including materials such as lime, organic amendments, and soil conditioners, function to create or maintain a physical environment favorable to production. Finally, protective inputs, such as pesticides and antibiotics, serve to prevent biotic injury to allocation-selected (A-selected) domesticates that have lost many of their natural defenses through artificial breeding (Cox 1984).

An important question in agroecology concerns the efficiency of utilization of these varied inputs, particularly in open agroecosystems. Do the natural climatic, edaphic, and biotic processes to which such agroecosystems are exposed constrain the beneficial effects of these inputs to a high degree, perhaps limiting the productivity of subsidized agroecosystems to a level comparable to that of natural systems? Or are natural constraints limited in scope, so that agricultural technology has ample opportunity to devise new systems of input application that can efficiently raise productivity to levels well above those shown by natural ecosystems?

In considering these questions we must remember that the biological productivity of agroecosystems —Net Primary Production (NPP)— is distinct from the yield of desired food materials, the latter having been the traditional focus of scientific interest and virtually the only feature of statistical record. From an agroecological perspective, however, we are interested in both the agroecosystem NPP and yield, relative to the NPP and other production statistics of natural ecosystems under comparable external environments. In addition, we must recognize that the utilization of inputs can be evaluated both in economic and biological terms, the former having been the evaluation emphasized in applied agriculture. Our agroecological interest, on the other hand, also extends to the absolute efficiency of various inputs, in terms of the effect of absolute quantities of the input on the NPP and yield of the agroecosystem.

In inquiring into the relation between productivity of agroecosystems and that of natural ecosystems we must recognize that in any environment natural productivity is limited in a hierarchical manner. For example, in a desert environment the immediate limiting factor for productivity is usually water. If this limitation is removed, a new limiting factor comes into play, perhaps nutrient availability. Likewise, if this limitation is taken away, still another relation comes into play at a higher level. Thus, when we examine the relationship of NPP of agroecosystems to that of natural systems, we are really asking where the maximum, or perhaps optimum, level of agroecosystem function lies in this hierarchy of natural limitation.

SUBSIDY AND STRESS IN AGROECOSYSTEMS

In a particular regional environment, ecosystems can be envisioned as being in various stages of development toward a regional climax state (Figure 1). The longest and slowest developmental process is that of primary succession; various secondary successional sequences may also exist, varying in duration and speed with the degree of disturbance that initiated them. Over shorter time periods the ecosystem also exhibits patterns of recovery from year-to-year climatic fluctuations and intrasystem disturbances less intense than those triggering overall secondary successional responses. Thus, even in a successionally mature system, net primary production (NPP) shows a pattern of fluctuation about the regional climax level, reflecting these latter influences.

Exploitation of ecosystem production, coupled with export of harvested materials, is a form of disturbance that inevitably reduces NPP below the regional climax level. Periodic unsubsidized exploitation, as in shifting cultivation, can lead to pulse stability at a lower NPP level, or to a pulsed pattern of ecosystem deterioration, depending on the length of the interval (fallow) between periods of exploitation (Figure 2). Contin-

Figure 1. Relationships of ecological succession, intrasystem stress, and climatic variability to annual net primary production (NPP) in natural ecosystems.

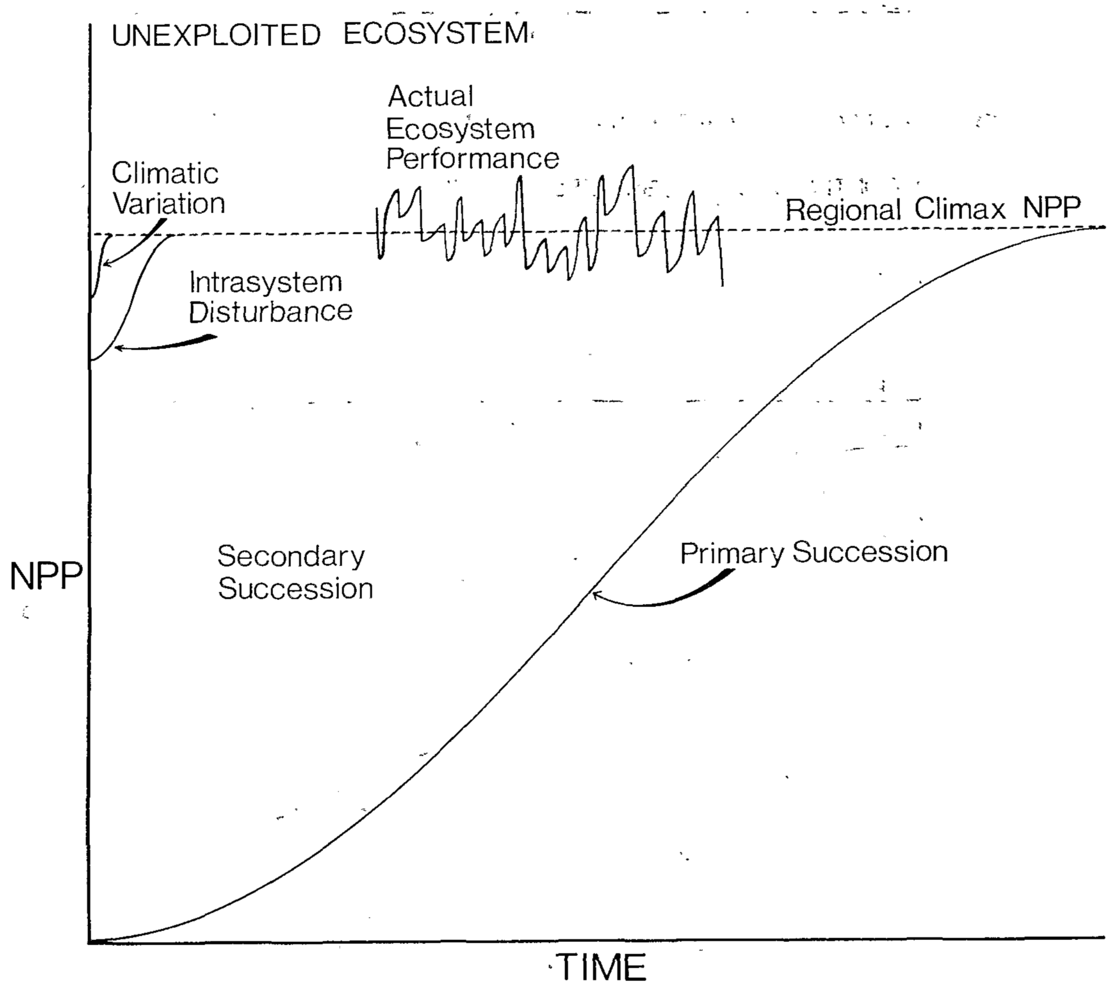


Figure 2. The relationship of discontinuous exploitation, alternating with periods of fallow (f) conditions, on net primary production (NPP) of ecosystems.

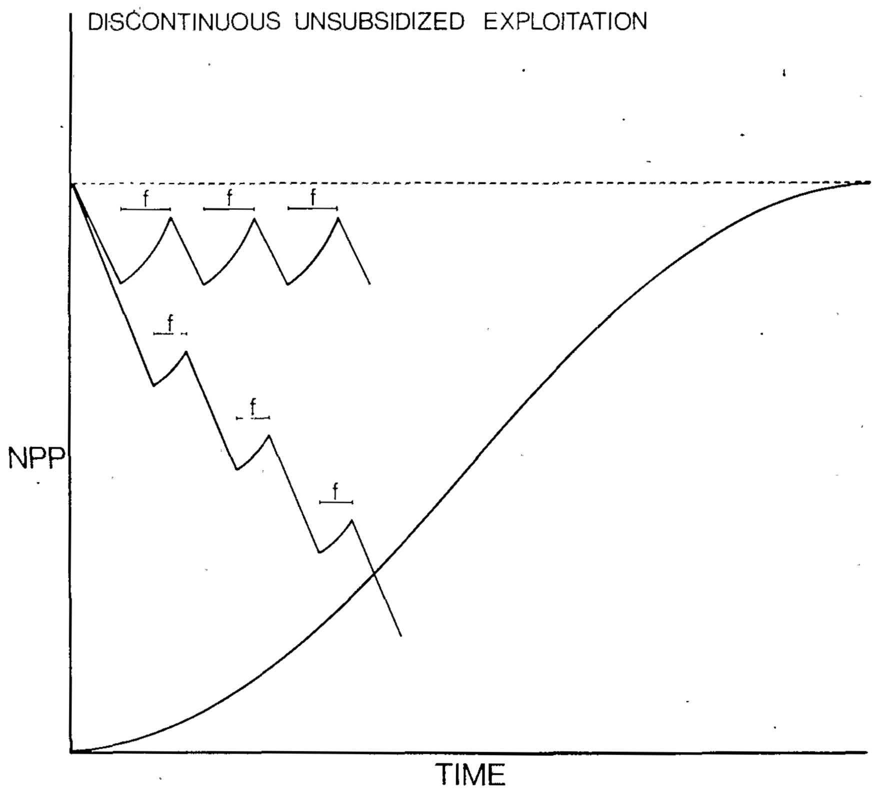
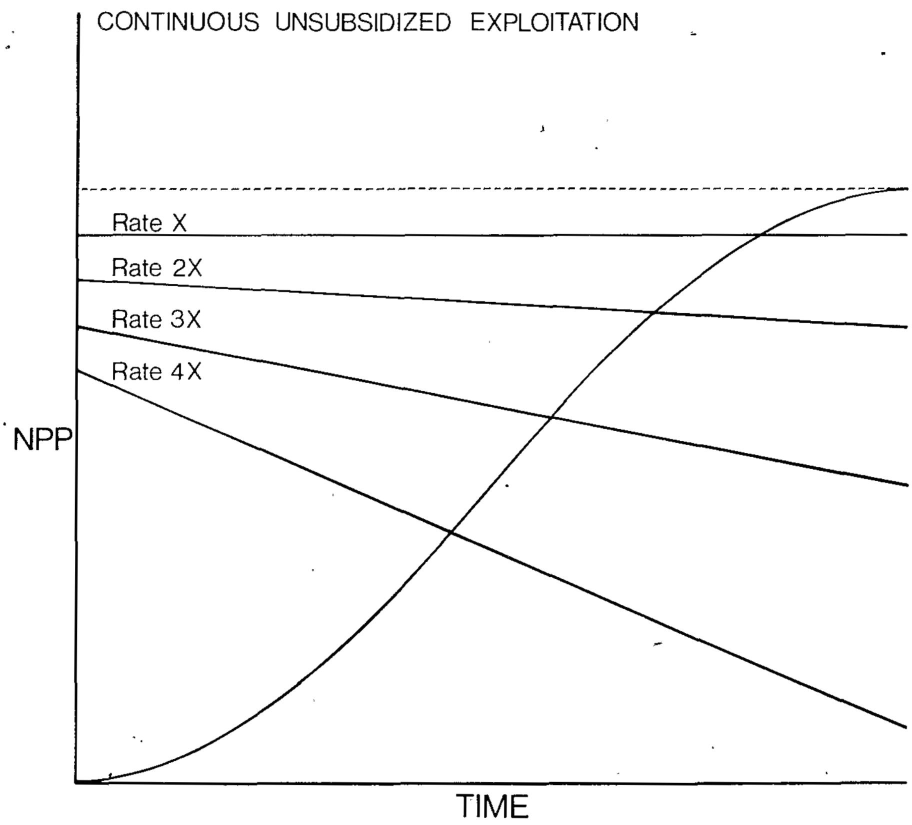


Figure 3. Effects of continuous unsubsidized exploitation on net primary production (NPP) of ecosystems.

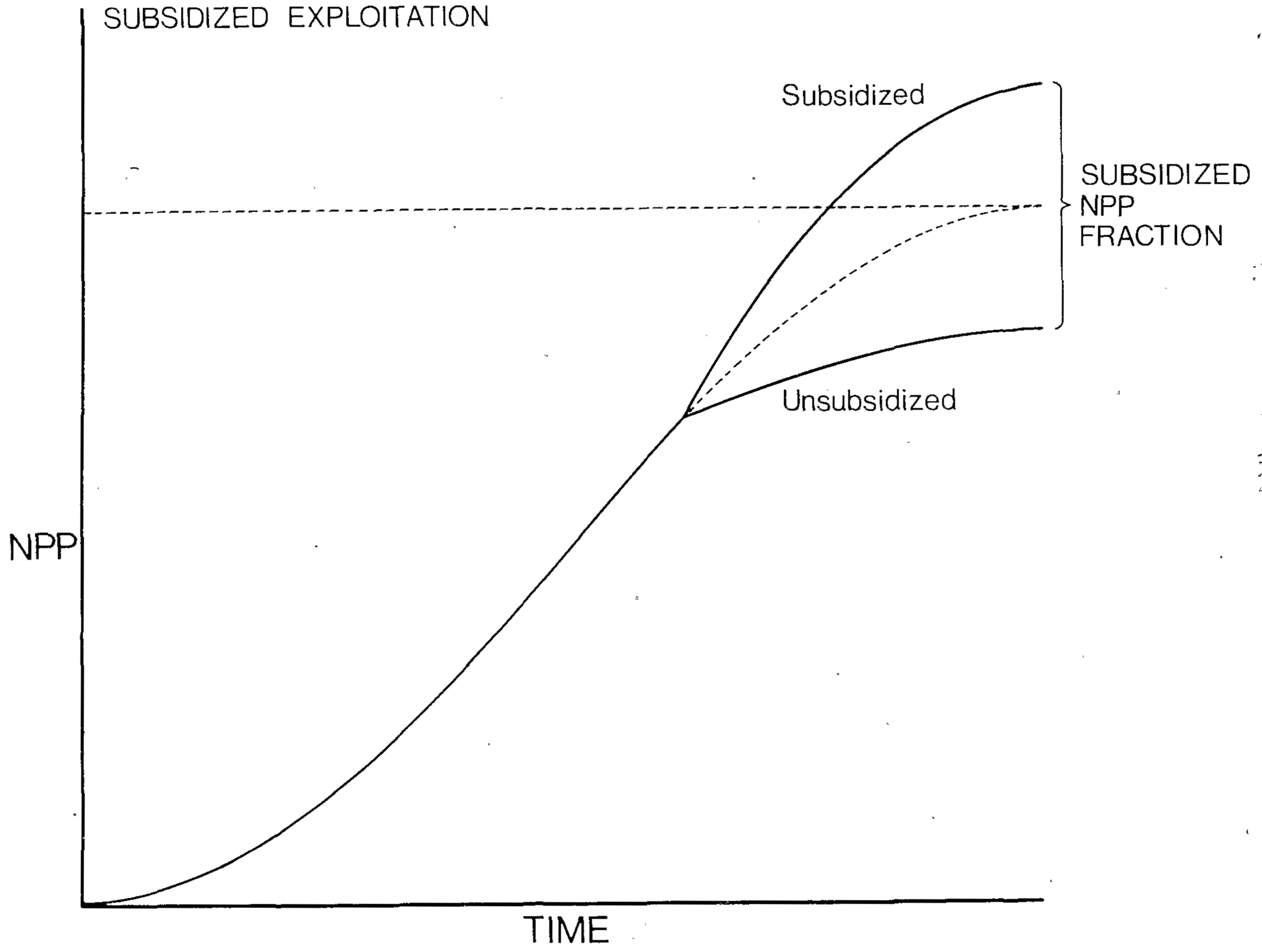


uous unsubsidized exploitation can likewise permit either a lower level of relatively stable NPP to exist, if the intensity of exploitation is low, or cause progressive deterioration of ecosystem organization and NPP, if it is too high (Figure 3).

With the application of external subsidies, a more complex situation is created (Figure 4). Although exploitation tends still to modify intrinsic ecosystem organization and reduce NPP, this effect is offset to some degree, and realized NPP may approach or even exceed that of the natural ecosystem. A certain fraction of this realized NPP can thus be considered subsidized NPP. Unfortunately, in this case, the extent of the degradation of the intrinsic organization of the original ecosystem is usually not apparent, since it is masked by the subsidized NPP fraction. Depending on the pattern of change through time in the quantities of subsidies being applied, a stable or even increasing level of realized NPP may be coupled with an improving, stable, or deteriorating level of intrinsic organization.

Few data exist for examining such relationships in natural ecosystems and agroecosystems in comparable environments. To gain some idea of the relationships involved, however, we shall examine production relationships for unsubsidized forages and for subsidized forages and crops. For the United States, statistics are available on the harvest of wild hay, which in most areas is cut from stands of natural (although not necessarily native) grasses and forbs that are neither fertilized nor irrigated (in the western states some wild hay areas are irrigated). Data on wild hay production are summarized for various counties and states in the periodic U.S. Census of Agriculture (at 4-5 year intervals), the most detailed recent compilation of such data being for 1969.

Figure 4. Subsidization and the subsidized net primary production (NPP) fraction of a continuously exploited ecosystem.



Wild hay production for various midwestern and eastern states (Figure 5) for which irrigation is nil or negligible bears a significant ($r = 0.455$, $P < 0.025$) correlation with NPP as estimated by the precipitation and annual temperature relationships given by Leith (1973). For these 28 states, the ratio of wild hay production to calculated NPP ranges from 0.14 to 0.32, averaging 0.20. This ratio —the fraction of calculated NPP that is harvested— tends to be higher than 0.20 in the Lake States and New England, and less than 0.20 in the South Atlantic and Gulf States.

For Indiana, which may be taken as an exemplary midwestern state, wild hay production in 1969 was 3.197 t / ha and equalled 22 % of the calculated natural NPP of 14.58 t/ha (Figure 6). Production of various forms of tame hay (alfalfa, small grain hay, and other cultivated forages), which received various amounts of fertilizers, exceeded 7 t / ha in some instances. The difference between tame hay and wild hay yields, expressed as a percentage of tame hay yields, may be considered as a rough estimate of the subsidized NPP fraction for this type of forage ecosystem. In Figure 6, in which tame hay NPP is related to fertilizer application, NPP plateaus near 7 t / ha, corresponding to a subsidized NPP fraction just below a value of 0.6. However, wild and tame hay yields are for aboveground material only. Belowground biomass and productivity, relative to aboveground values, vary greatly with temperature, moisture conditions, fertility, and other factors (Davidson 1969, Reynolds and Thornley 1982). In general, root / shoot biomass ratios decrease as conditions become more favorable for root activity. If, in these lightly fertilized and unirrigated stands, belowground NPP approaches 50 % of total NPP, the plateau of tame hay yield would be close to that of regional climax NPP.

Figure 5. The relation of wild hay yield to calculated regional net primary production for 28 eastern and midwestern states (U.S.A.) in 1969. Data from the U.S. Census of Agriculture, 1969.

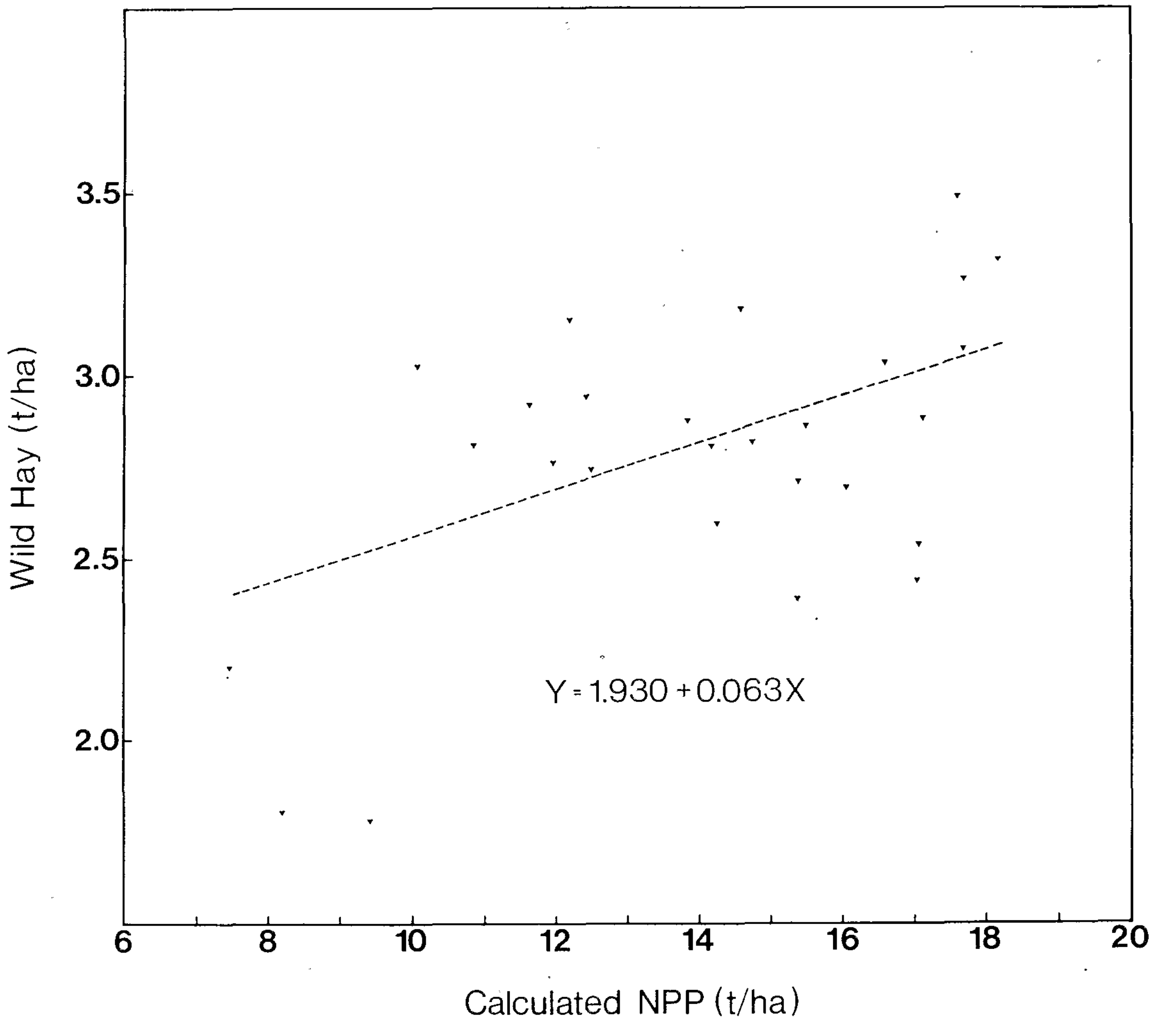
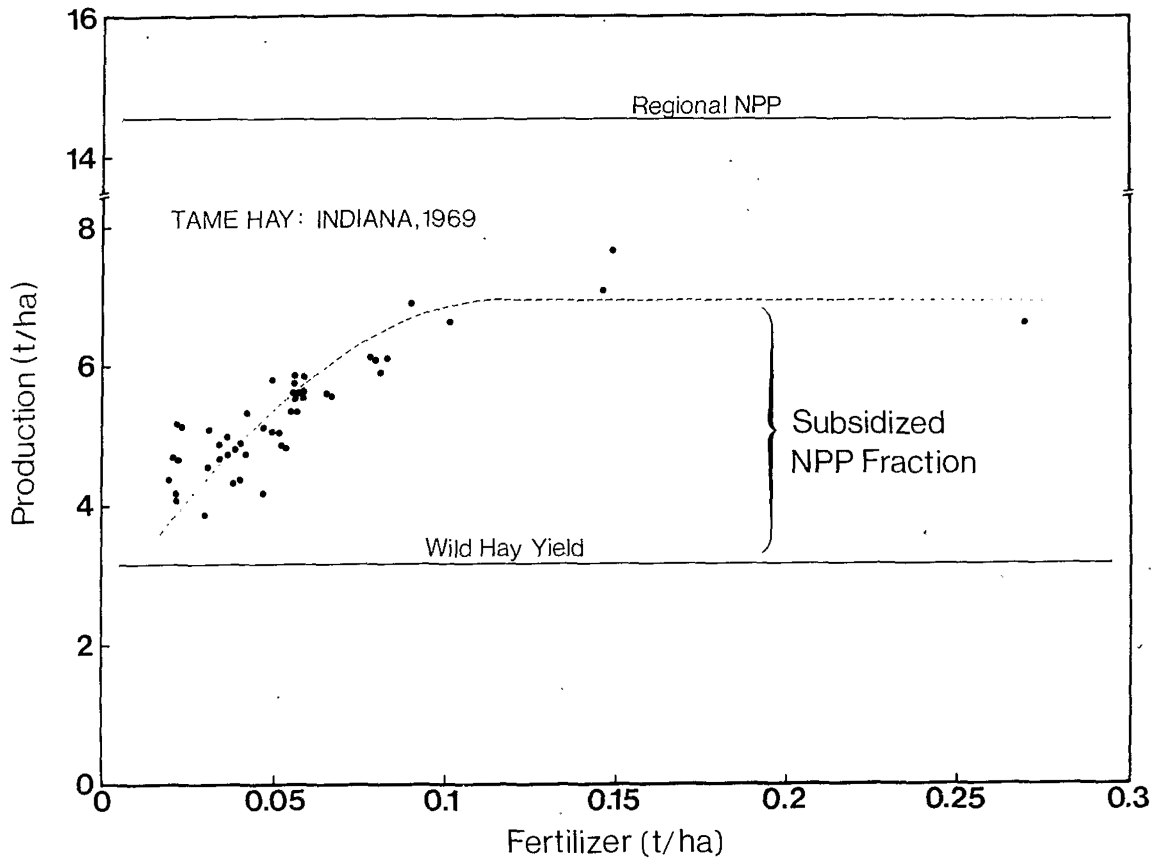


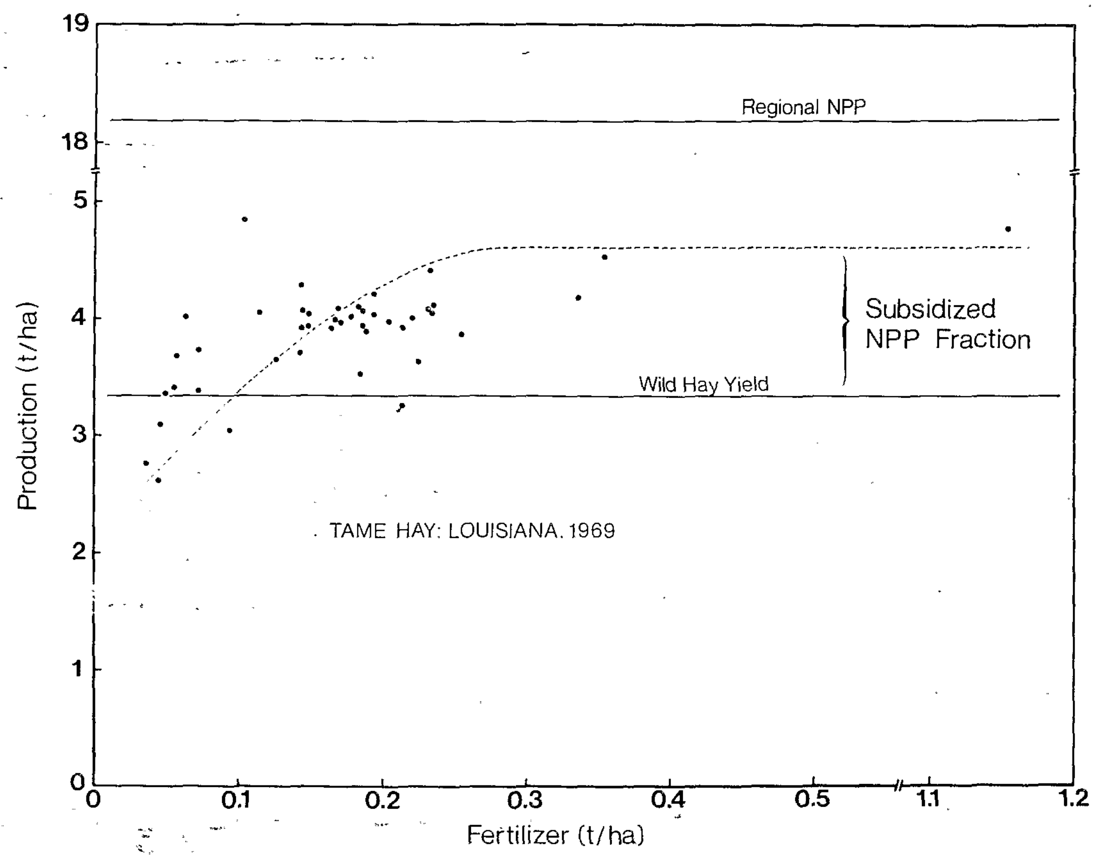
Figure 6. Yield of tame hay stands in Indiana in relation to fertilizer application levels (1969). Data from the U.S. Census of Agriculture, 1969.



To assess the influence of deterioration in ecosystem organization on production relationships in agroecosystems, the situation in Indiana can be contrasted with that in Lousiana. In the Delta Region of the United States, which includes Louisiana, soil erosion averages 46.8 t / ha annually (Cox 1984). However, the more favorable temperature and precipitation regimes permit wild hay yield to equal 3.31 t / ha, a value about 3.5 % higher than that for Indiana, and equalling about 18 % of the calculated natural NPP for Louisiana conditions. The response curve of tame hay production in Lousiana (Figure 7), however, plateaus at about 4.5 t / ha, far below the value of 18.17 t / ha that should be attained if agroecosystem NPP, under high subsidy levels, equalled that of natural ecosystems. Even if the highest observed values are doubled to take into consideration the belowground production of tame hay stands, the subsidized NPP fraction is still well below calculated natural levels. Furthermore, in some cases subsidized tame hay yields fall substantially below those for wild hay (Figure 7).

This pattern is reinforced by the trend observed in tame hay yields for Indiana and Louisiana between 1920 and 1974, using data from the U.S. Censuses of Agriculture conducted during this period. Although data on fertilizer use on forage crops do not exist for most of these censuses, it is presumed that both states experienced increased use of fertilizers and other productive inputs through this period. For Indiana, a significant regression of increased production on time exists (b = 0.025, $F_{1,8}$ = 27.05, $P < 0.001$). while for Louisina this regression lacks significance (b = 0.011, $F_{1,9}$ = 5,30, $P > 0.05$). Thus, increased utilization of productive inputs has improved tame hay yields in Indiana, where the tendency toward erosional degradation of the soil is low, while in Louisiana input intensification seems to have functioned mainly to offset continuing agroecosystem deterioration.

Figure 7. Yield of tame hay stands in Louisiana in relation to fertilizer application levels (1969). Data from the U.S. Census of Agriculture, 1969.



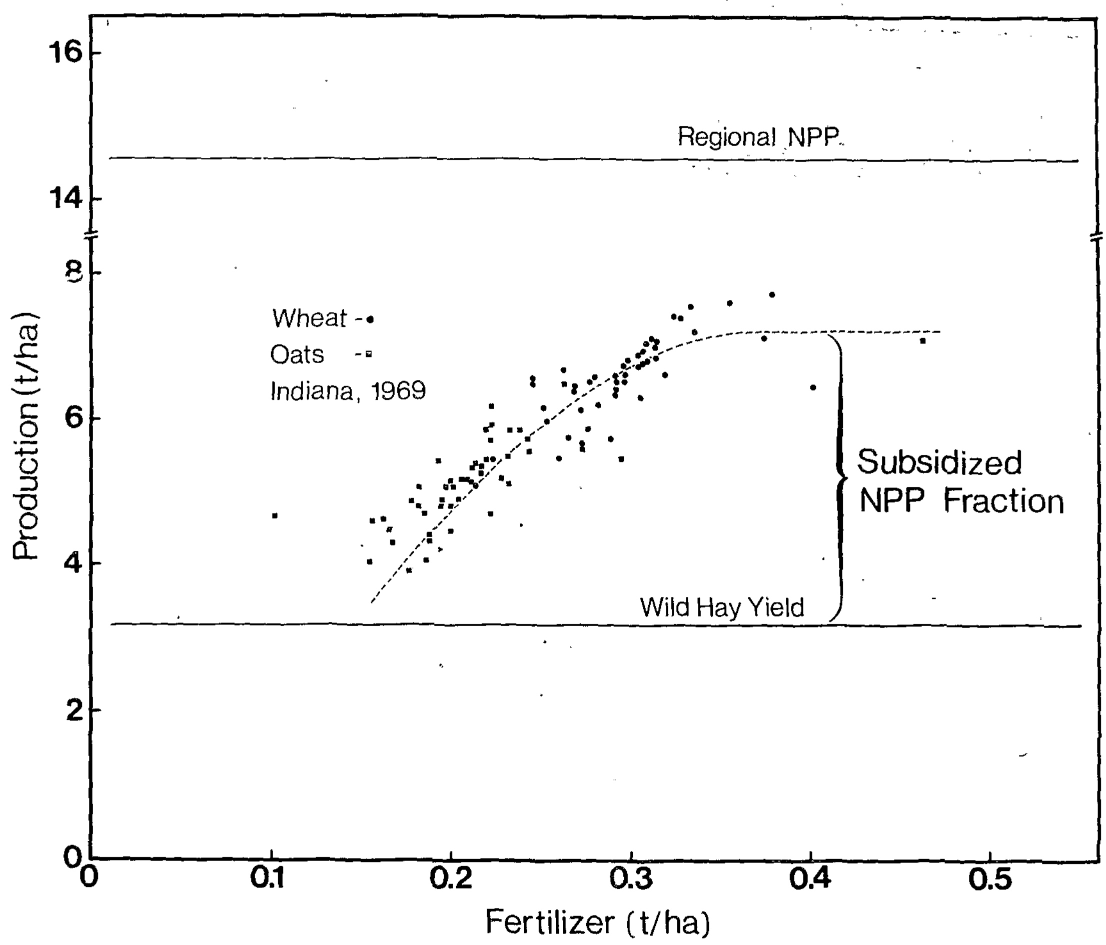
Cox (1984) concluded that this pattern was shown for crops in general throughout the United States. For the period 1960-78, the regression slope of total per-acre crop yield on per-acre fertilizer use showed a close relationship to soil erosion levels for different crop production regions, being highest for regions of low erosion. Cropland erosion has once again become recognized as a problem of major significance in the United States, where the average rate of soil loss is estimated to be 7.0 t / acre annually, while soil formation occurs at a rate of only about 0.5 t / acre annually (OTA 1982). Soil erosion, furthermore, is accompanied by several other detrimental impacts of modern agricultural technology, including soil compaction, salination, ground water depletion, land subsidence, soil organic matter depletion, impoverishment of soil microbiota, and detrimental changes in soil chemistry. The depletion of soil organic matter is one of the least recognized, but perhaps most significant, aspects of agroecosystem deterioration. Lucas *et al.* (1977), for example, note that soil carbon levels are closely related to crop production, an increase in soil carbon from 1.0 to 2.15 % increasing the yield potential for corn by about 25 %.

These relationships correspond in a general way to the subsidy-stress gradient considered by Odum *et al.* (1979) and Smathers *et al.* (1983). This formulation suggests that usable inputs have a subsidizing effect up to a certain intensity of application, but beyond this intensity they exert stress upon the system, reducing its performance and eventually causing replacement or complete destruction of the ecosystem. The subsidy-stress relationship, as presently formulated, does not adequately take into account the fact that effects of some inputs are immediate, increasing or decreasing the performance (e. g., NPP) of the ecosystem during the production season immediately after their application, while other inputs have a long-term beneficial or degrading impact. When the performance of an agroecosystem is related to the cumulative effect of degradational influences over a long period, it is not easily placed on a scale of perturbation intensity that can also accomodate immediate subsidy or stress influences of other inputs. As noted by Odum *et* *al.* (1979), the subsidy-stress gradient must interact with a successional gradient. A combination of concepts relating to these two gradients may therefore provide a better basis for describing the influences of inputs on agroecosystem performance.

SUBSIDIZED PRODUCTION AND NATURAL PRODUCTIVITY

We shall now examine relationships between subsidized productivity of agroecosystems and the productivity of the natural systems that they have replaced. As noted earlier (Figure 6), at maximum levels of fertilizer application, tame hay yields for Indiana plateau at a subsidized NPP fraction just under 0.6. Subsidized NPP curves for wheat and oats show a similar pattern (Figure 8). To obtain the values in this figure, grain yield figures were adjusted by harvest index values of 0.39 for wheat and 0.41 for oats (Singh and Stoskopf, 1971) to give an estimate of total aboveground production. Harvest index is influenced by a variety of cultural factors (Donald and Hamblin, 1976) and has been subject to considerable selectional modification in crop breeding (Evans, 1980), so that these harvest index corrections should be considered only approximate. Wheat and oats, subject to different average levels of fertilizer application as a consequence of the differential economic value of the harvestable grain, fall on a common curve, different from that for tame hay (Figure 6) but plateauing at about the same level. In the case of these annual crops, receiving appreciable fertilizer applications, belowground production is probably appreciably less than aboveground production, so that total crop agroecosystem NPP at maximum fertilization levels is almost certainly less than that for mature natural systems (Leith, 1973). For Indiana, potential natural NPP levels calculated by relationships based on mean annual temperature and mean annual precipitation are about equal, 15.40 and 14.58 t/ha, respectively (Leith, 1973). Thus, we may consider that at levels

Figure 8. Estimated NPP for wheat and oats in Indiana (1969) in relation to fertilizer application levels. Data from the U.S. Census of Agriculture, 1969.



below this range, production is limited probably by nutrient availability.

Wheat, oats, and forages commonly grown in Indiana are all C_3 species. If we examine the subsidized NPP curve for corn (maize), a C_4 species, a higher plateau of agroecosystem performance is seen (Figure 9). In this figure, grain yield data were adjusted with a harvest index value of 0.40 (Donald and Hamblin, 1976). The plateau of aboveground yield given with this correction lies slightly above 17 t/ha; even without additional correction for belowground production, this level substantially exceeds the calculated natural NPP level for Indiana (14.58 t/ha). If the root/shoot ratio for this heavily fertilized crop were as low as 0.2, total agroecosystem NPP would exceed 20 t/ha. This analysis does not take into account differential requirements for inputs other than fertilizers, particularly protective inputs, that are essential for production of corn, or for the differential long-term impacts of corn cultivation on agroecosystem conditions (as through erosion). However, it does show that under specific conditions subsidized yields of certain crops may considerably exceed the levels of production seen in mature natural ecosystems.

If we examine tame forage yields in a region where moisture is often a limiting factor, such as Oregon, we see that irrigation fraction (the proportion of hay acreage irrigated) does not yield a curve of subsidized NPP which plateaus as those previously examined (Figure 10), while the relationship with fertilizer use does (Figure 11). The subsidized NPP for tame hay in Oregon plateaus at about 7 t/ha. If this plateau is doubled to take into account belowground production, the yield plateau would substantially

Figure 9. Estimated NPP for corn (maize) stands in Indiana (1969) in relation to fertilizer application levels. Data from the U.S. Census of Agriculture, 1969.

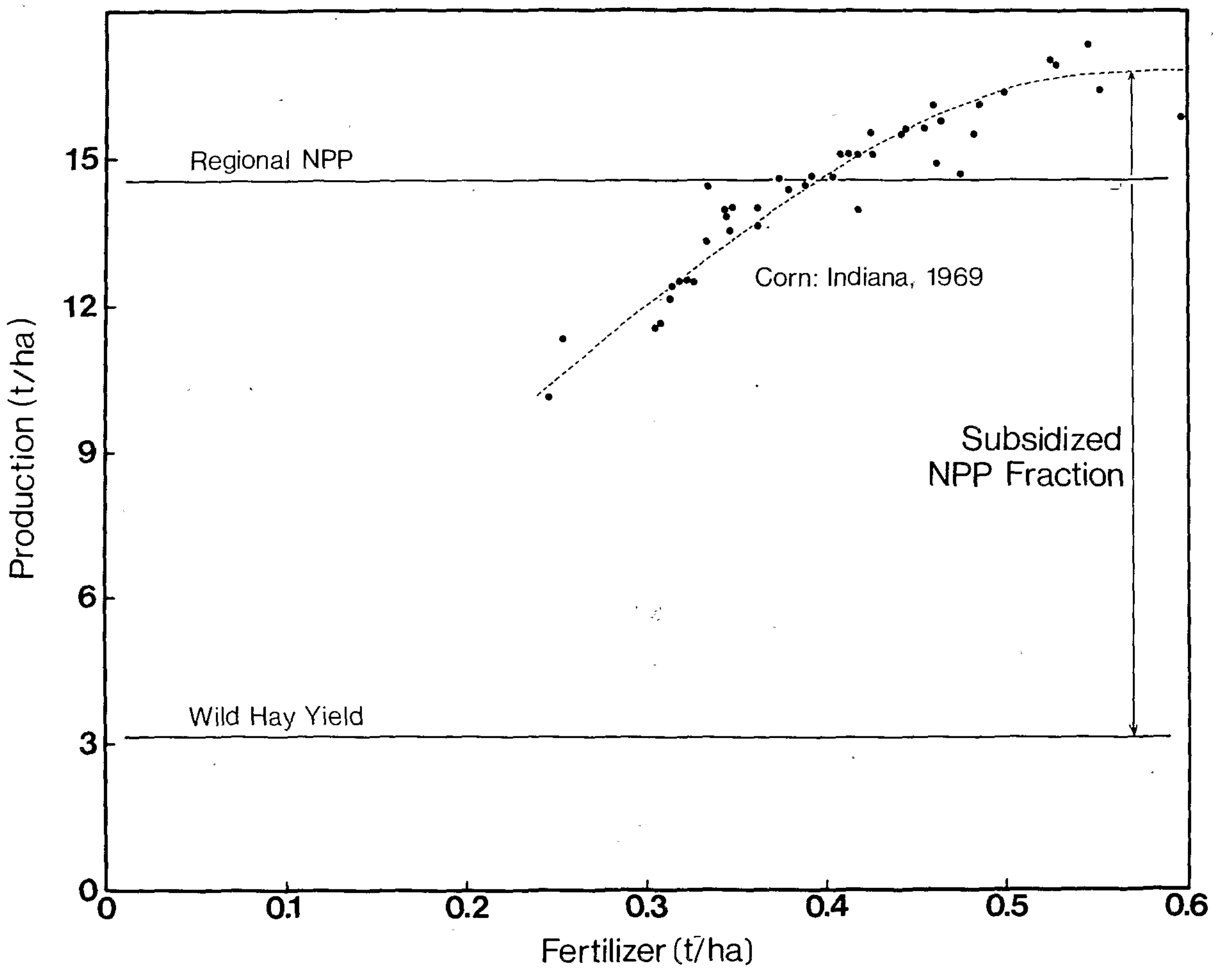


Figure 10. Yield of tame hay stands in Oregon (1969) in relation to irrigation fraction. Data from the U.S. Census of Agriculture, 1969.

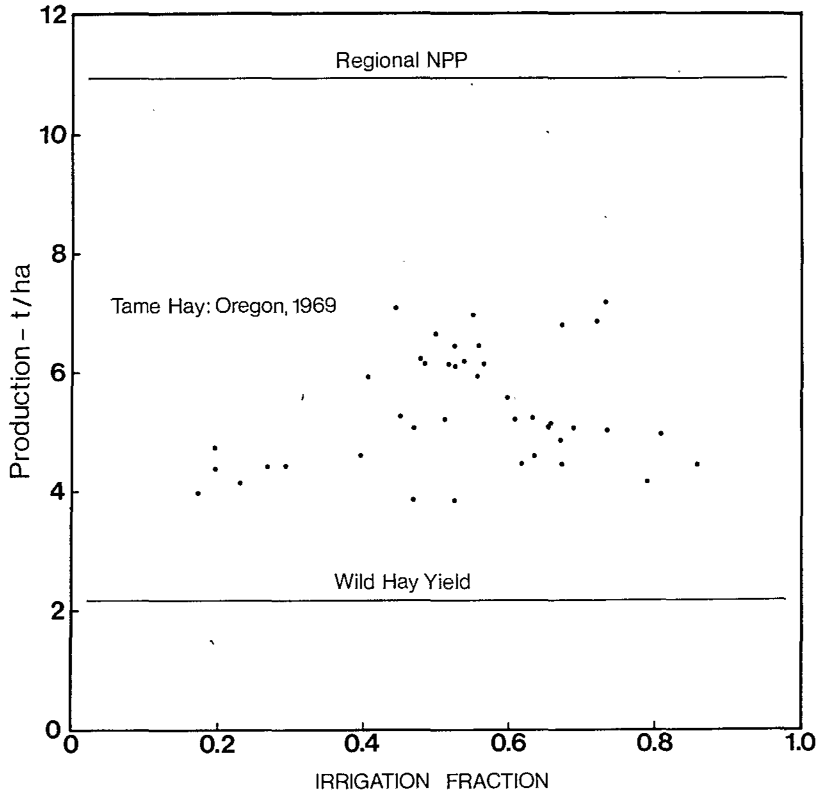
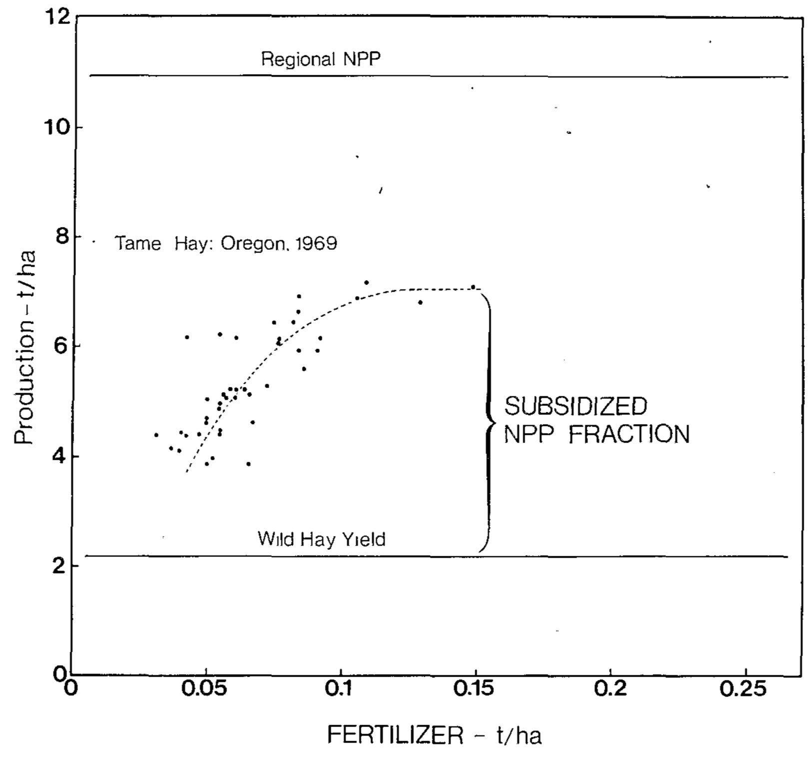


Figure 11. Yield of tame hay stands in Oregon (1969) in relation to fertilizer application levels. Data from the U.S. Census of Agriculture, 1969.



exceed the NPP level calculated for natural ecosystems in Oregon on the basis of annual precipitation (10.95 t/ha) and approximate that based on annual temperature (13.27 t/ha). Thus, irrigation functions in a slightly different fashion than fertilizer inputs; it mitigates a limiting factor of the physical environment, permitting other productive inputs to exhibit their differential influences.

To carry the moisture limitation situation to its extreme, we may exmine tame forage production in the Imperial Valley of California. Here, the natural NPP level predicted on the basis of mean annual precipitation is very small —0.28 t/ha— while that predicted on the basis of mean annual temperature is very high —29.84 t/ha. Essentially all forage acreage in the Imperial Valley is irrigated, and production is year-round, yielding (1969) about 13.52 t/ha. Furthermore, if the realized yield is doubled to take into consideration belowground production, tame forage NPP approaches the value calculated on the basis of annual temperature.

Thus, it appears that the use of basic inputs of irrigation water and fertilizer in temperate zone agroecosystems, in combination with other productive inputs, are able to raise NPP to levels close to those of the natural ecosystems of the region. Reaching natural levels is probably realized, however, only on agricultural land that has not been severely degraded, as many areas have through soil erosion. Furthermore, it appears that the introduction of crop species from regions with higher natural levels of potential NPP can permit levels of agroecosystem NPP above those characteristic of the region itself, provided that both productive and protective inputs can be provided.

INPUT UTILIZATION EFFICIENCY

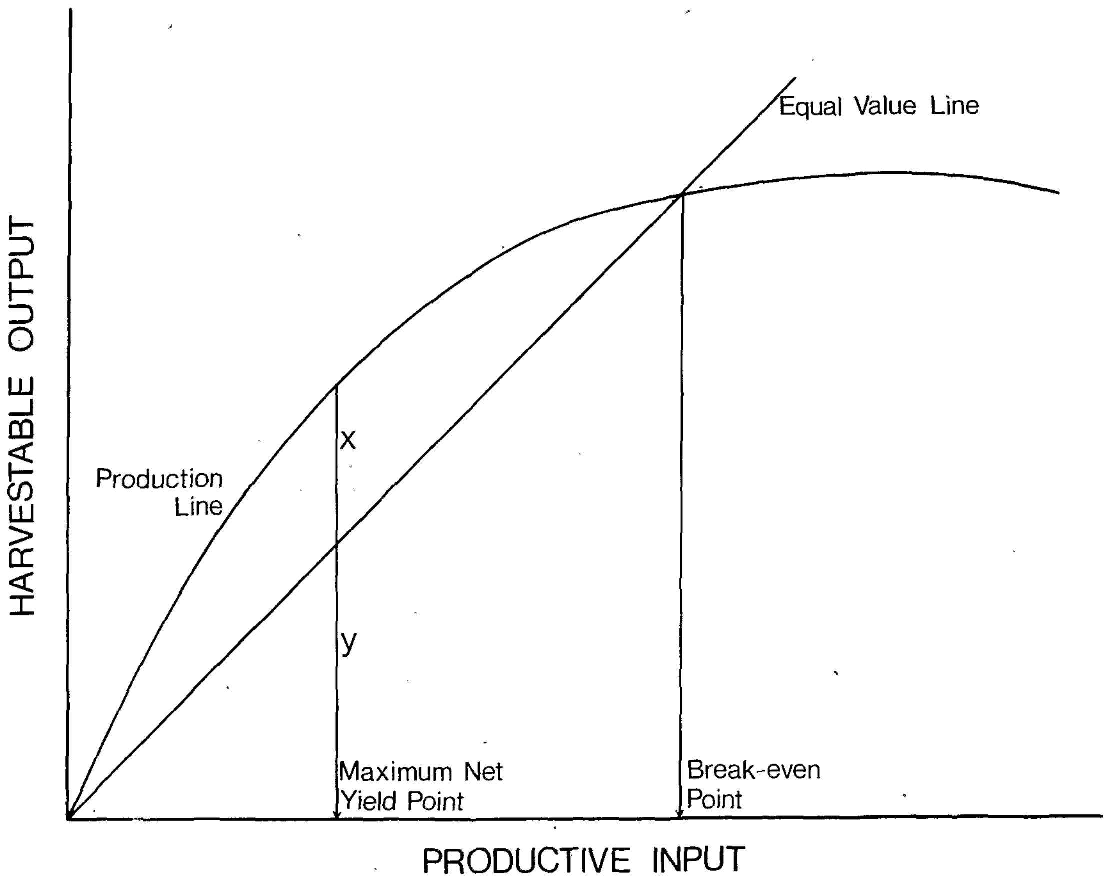
A question of considerable applied importance concerns whether or not the NPP level at which maximum efficiency of inputs is realized bears a close relationship to the NPP of natural ecosystems. The point of maximum efficiency for a given input can be determined objectively from a standard output-input ("catch-effort") curve (Figure 12) in which inputs and outputs are scaled in common units (cost, energy value, nutrient value, or other). In the case illustrated, yield is zero when input is zero. Often, however, a significant yield exists for zero input; in this case the line of equal value originates from this intercept. The point of maximum net yield is the point of tangency on the yield curve of a line parallel to the equal-value line. For some comparisons (energy, nutrient content) the equal value line may lie above the production curve. At the point of maximum net yield the value x will be maximal (or least negative, if the equal value line lies above the production curve), but the ratio x/y of net yield to cost will not necessarily be maximal. The maximum efficiency, in the latter sense, is given by the point of tangency on the production curve of a line originating at the intercept (Fluck and Baird, 1980). This latter point gives a true definition of the point of maximum efficiency even when the axes are scaled in different units (e. g., $ of yield vs tons of fertilizer). It should also be noted that the point of maximum efficiency defined in this manner will always be at zero input if the production curve is convex; only when the production curve is sigmoid will the point of maximum efficiency lie above zero input.

Many analyses have been done of input-output efficiency in economic terms, since the behavior of American agriculture is strongly determined by the immediate relative cost of various inputs, particularly labor and its alternatives (Edens and Koenig, 1980). As Hill and Ramsay (1977) note, "Progress in agriculture has been largely energy addictive". From an agroecological viewpoint, however, it is important to consider aspects of efficiency beyond those of immediate cost and income relationships.

Although it is difficult to explore efficiencies of input use in U.S. agriculture directly, using published statistics, we can examine the economic efficiency of input use for farms of different size. If we examine data from the U.S. Censuses of Agriculture for sales of agricultural products per acre and for production expenses per acre, we find that the maximum efficiency, in the sense of maximum net income per unit input cost, is for farms of intermediate size. For example, for Indiana in 1978, the maximum profit/cost ratio was for farms with a mean size of 670 acres. If we examine the same relationship for other censuses over recent decades, we find that the farm size of maximum efficiency has increased steadily, from 238 acres in 1959 to 354 acres in 1969.

The primary cause of the shift in average farm size in the U.S. in recent decades is well known — the disproportionate increase in the cost of labor. For Indiana, in 1959, data for farms of different size reveal that labor costs are inversely related to the profit / cost ratio for farming operations ($b = 0.012$, $F_{1,10} = 6.304$, $P < 0.05$). In 1978, this relationship had changed somewhat, and labor costs were no longer significantly related to profit / cost ratio. However, fertilizer expenses showed a significant positive relationship

Figure 12. Maximum net yield and breakeven points for harvestable output relative to productive input in agroecosystems.



with profit/cost ratio (b = 0.041, $F_{1,10}$ = 8.99, P < 0.025). Interestingly, in spite of this relationship, the rate of increase in annual use of fertilizers in the United States has slowed recently (Hargett and Berry 1983). In 1982, total annual fertilizer use dropped to 48.7 million tons, from 54.0 million tons in 1981. In general, for the period 1972-82, rates of annual increase in fertilizer use have been less that half of those, for all fertilizer types, than for the period 1962-72. This trend suggests that cost relationships for fertilizers have begun to inhibit use of an input category that is basic to biological production and formerly directly correlated with efficiency of production in agroecosystems.

This fact emphasizes one of the most important considerations in the evaluation of efficiency of input performance in agroecosystems: stablility of intrinsic ecosystem organization. In most traditional evaluations of efficiency, no consideration is given to whether or not deterioration of conditions important to the production process has accompanied the measured yield response to the use of measured inputs. From an ecological point of view, however, efficiency must be evaluated under conditions that maintain the productive characteristics of soils, intrinsic biological control, and other aspects of ecological organization at stability.

There is little reason to suppose that economic input-output analyses will reveal a close relationship between points of maximum input efficiency and natural ecosystem function. Thus, we need evaluations of input efficiency in purely ecological terms. For these input analyses, as well, we must recognize that inputs of equal value may be utilized with differing degrees of agricultural skill, so that they stimulate different levels of output. However, we may hypothesize that skillful use of various types of productive inputs will achieve maximum efficiency at a level of agroecosystem function corresponding to that of natural ecosystems limited by the same factors.

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