WORKING PAPER

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University of Lüneburg
Working Paper Series in Economics

No. 146

October 2009

www.leuphana.de/vwl/papers

ISSN 1860 - 5508

The relationship between resilience and sustainable development of ecological-economic systems

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draft version, September 2009

Abstract: Resilience as a descriptive concept gives insight into the dynamic properties of a system. Sustainability as a normative concept captures basic ideas of inter- and intragenerational justice. In this paper we specify the relationship between resilience and sustainable development. Based on an ecological-economic model where two natural capital stocks provide ecosystem services that are complements for human well-being, we derive conditions on the dynamics of the ecological-economic system and the sustainability criterion, such that a) resilience of the system in a given regime is both necessary and sufficient for sustainable development, b) resilience of the system in a given regime is sufficient, but not necessary, c) resilience of the system in a given regime is necessary, but not sufficient, and d) resilience of the system in a given regime is neither necessary nor sufficient for sustainable development. We conclude that more criteria than the resilience of the current state of the system have to be taken into account when designing policies for sustainable management of ecological-economic systems.

Keywords: ecosystem resilience, sustainable development, management of ecological-economic systems

JEL-Classification: Q20, Q56, Q57

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1 Introduction

Speaking about resilience and sustainable development is speaking about two highly abstract and complex concepts, each of which has a great variety of interpretations and definitions. Here we adopt what seems to be the most general and at the same time most widely accepted definitions of resilience and sustainable development. We understand sustainable development as the Brundtland Commission defines it as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987)[1]. In this definition, sustainability is a normative concept capturing basic ideas of inter- and intragenerational justice. With respect to obligations toward future generations, the primary question of sustainable development is to what extent natural capital stocks have to be maintained to enable future generations to meet their needs[2].

In contrast, resilience is a descriptive concept. In a most common definition resilience is thought of as "[...] the magnitude of disturbance that can be absorbed before the system changes its structure by changing the variables and processes that control behaviour" (Holling & Gunderson 2002: 4). Here, a system may flip from one basin of attraction into another one as a result of an exogenous disturbance. If the system will not flip due to exogenous disturbance in a given time span the system in its initial state is called resilient. With this notion, resilience is not quantitatively measured, but qualitatively classified: a system in a given state is either resilient, or it is not (Holling 1973).

In the literature, many connections have been drawn between resilience and sustainable development (see e.g. Folke et al. 2004, Walker & Salt 2006, Mäler 2008). For example, in some cases authors have used the notions of resilience and sustainable development almost interchangeably: "A system may be said to be Holling-sustainable, if and only if it is Holling-resilient" (Common & Perrings 1992: 28) or similarly: "A resilient socio-ecological system is synonymous with a region that is ecologically, economically, and socially sustainable" (Holling & Walker 2003: 1). Levin et al. (1998) claim in general that "[r]esilience is the preferred way to think about sustainability in social as well as natural systems" (Levin et al. 1998), thus suggesting basically an equivalence of resilience and sustainable development.

In some cases, resilience is seen as a necessary precondition for sustainability and sustainable development. For example, Lebel et al. (2006: 2) point out that "[s]trengthening the capacity of societies to manage resilience

[1]Evidently, as definitions are not universally and are appropriate for a certain objective only (Jax 2002), the relationship between resilience and sustainable development, depends on the given definitions of these two terms.

[2]The term "natural capital" was established to distinguish services and functions of ecosystems from other capital stocks (Pearce 1988).

is critical to effectively pursuing sustainable development". Similarly, Arrow et al. (1995: 93) conclude that "[. . .] economic activities are sustainable only if the life-support ecosystems upon which they depend are resilient", and also Perrings (2006: 418) states that "[a] development strategy is not sustainable if it is not resilient: i.e. if it involves a significant risk that the economy can be flipped from a desirable state (path) into an undesirable state (path) and if that change is either irreversible or only slowly reversible". This does not mean, however, that resilience might be an objective of its own. For, it has been noted that: "[r]esilience, per se, is not necessarily a good thing. Undesirable system configurations (e.g. Stalin's regime, collapsed fish stocks) can be very resilient, and they can have high adaptive capacity in the sense of re-configuring to retain the same controls on function" (Holling & Walker 2003).

While systems with multiple stable states are widely discussed, a systematic analysis of the relationship between the concepts of resilience and sustainable development in a system with multiple stable states has not yet been conducted. In this context the statements above do not take into account the following possibilities: if a system flips from an undesirable state into a desirable state, or from a desirable state into another desirable state, a system strategy might be sustainable, even though it is not resilient. As a consequence, one may conclude that resilience is neither desirable in itself nor is there any justification of the conclusion that resilience in general might be taken as a necessary or sufficient condition for sustainable development.

In order to clarify the different possibilities and to investigate the conditions of how resilience and sustainable development are interlinked, we present an ecological-economic model of two natural capital stocks providing ecosystem services that are complementary in the satisfaction of human needs.

It is not meant to represent a "real" complex ecological-economic system. But in contrast to other models presented in the context of resilience of ecological-economic systems, like the shallow lake model (e.g. Scheffer 1997, Mäler et al. 2003) or rangeland models (e.g. Perrings & Stern (2000), Anderies et al. 2002, Janssen et al. 2004)), it features more than two basins of attraction and the possibility of more than one desirable state. In traditional models of bistable systems only two relationships of resilience and sustainable development are possible: (i) a situation in which the system is resilient in a desired state such that the systems' resilience has to be maintained for sustainable development, and (ii) a situation in which the system is resilient but is currently not in a desired state, such that resilience prevents a sustainable development. A situation in which the system is not resilient in a desired state but nevertheless on a path of sustainable development cannot - by construction of the model - possibly occur.

The outline of the paper is as follows. We present a simple ecological-economic model of two natural capita stocks (Section 2), and discuss key issues of the relationship between resilience and sustainable development in systems with multiple stable states. Based on the definitions given above, we will distinguish four cases of the relationship of resilience and sustainable development and specify general conditions for each type of relationship between resilience and sustainable development (Section 3). We draw conclusions concerning the sustainable management of ecological-economic systems in Section 4.

2 A simple ecological-economic model with multiple equilibria

The model describes the use of two natural capital stocks - fish and timber - and features multiple equilibria with different domains of attraction. The dynamics of the two stocks of fish (x) and wood (w) are described by the following differential equations, referring to the growth of the stocks of fish $\dot{x}$ and timber $\dot{w}$:

$$\dot{x} = f(x) - C = r_x \left(1 - \frac{x}{k_x} \right) x - C \tag{1}$$

$$\dot{w} = g(w) - H = r_w \left(1 - \frac{w}{k_w} \right) w - H \tag{2}$$

where r_i denotes the intrinsic growth rates and k_i the carrying capacities of the stocks of fish ($i = x$) and timber ($i = w$), respectively. The differential equations (**??**) and (**??**) are independent because, by assumption, the two stocks are ecologically independent, although, of course, in reality ecological interactions may exist. As a consequence, interactions of the stock dynamics are only due to the interrelated harvests of fish and timber. C and H denote the aggregate amounts of harvested fish and timber, $f(\cdot)$ and $g(\cdot)$ describe the intrinsic growth of the two stocks, which we assume as logistic for simplicity. The specification of the growth functions $f(x)$ and $g(w)$ as logistic is by no means essential for the results driven below. But using a well-known functional form of the growth functions helps to clarify the argument.

Society consists of n-identical utility-maximizing individuals who derive utility from the consumption of manufactured goods (y) as well as from the consumption of fish (c) and timber (h). We assume that all three goods are essential for individual well-being. The utility function of a representative household is:

$$u(y, c, h) = y^{1-\alpha} \left[c^{\frac{\sigma-1}{\sigma}} + h^{\frac{\sigma-1}{\sigma}} \right]^{\alpha \frac{\sigma}{\sigma-1}}. \tag{3}$$

Both natural capital stocks are complements in satisfying human needs, which is modeled by the assumption of $\sigma < 1$. The household´s elasticity of marginal utility for consumption of natural goods is given by $\alpha \in (0,1)$, and σ is the elasticity of substitution between the consumption of fish and timber.

There are m_x identical fish-harvesting firms and m_w identical timber-harvesting firms. These numbers are endogenously determined according to market conditions in these two sectors. Let e_x and e_w denote the effort, measured in units of labor, spent by some representative fish-harvesting-firm and some representative timber-harvesting-firm, respectively. Suppose that profit-maximizing firms can harvest the resource species from their natural stocks under open-access to ecosystems and sell these ecosystem services as market products to consumers. Assuming Gordon-Schaefer production functions, the amounts of fish and timber harvested from the respective stocks by individual firms are described by:

$$c^{prod} = v_x x e_x \tag{4}$$

$$h^{prod} = v_w w e_w, \tag{5}$$

with v_x, v_w denoting the productivity of harvesting fish and timber, respectively and e_x, e_w as the effort in units of labor. After deriving the open-access aggregate harvest amount C and H of fish and timber as functions of the respective resource stock (see Appendix) we can insert them into the differential equations (**??**) and (**??**). The dynamics of the ecological-economic system in a general market equilibrium where profit-maximizing harvesting firms have open access to ecosystems is then described by the following system of coupled differential equations:

$$\dot{x} = f(x) - n\alpha\lambda \frac{(v_x x)^{\sigma}}{(v_x x)^{\sigma-1} + (v_w w)^{\sigma-1}} \tag{6}$$

$$\dot{w} = g(x) - n\alpha\lambda \frac{(v_w x)^{\sigma}}{(v_x w)^{\sigma-1} + (v_w w)^{\sigma-1}}. \tag{7}$$

These dynamics of the ecological-economic model are represented by the following state-space diagram (Figure 1) for parameter values $p_x = p_w = 0.5$, $k_x = k_w = 1$, $v_x = v_w = 1$, $\alpha = 0.6$, $\sigma = 0.4$ and n = 1. The green line is the isocline for $\dot{x} = 0$, the red line is the isocline for $\dot{w} = 0$. Left (right) of the $\dot{x} = 0$-isocline the dynamics are characterized by $\dot{x} > 0$ (< 0). Likewise, below (above) the $\dot{w} = 0$-isocline the dynamics are characterized by $\dot{w} > 0$ (< 0). In each segment of the state space, the green and red arrows indicate this direction of dynamics. Point A denotes an unstable equilibrium where $x = w = 0$, B and C are locally stable equilibria with $x = 1$, $w = 0$ and $x = 0$, w

= 1 respectively. Points E and F are saddle point equilibria. Five domains of attraction exist: The domain of attraction of equilibrium E is the blue saddlepath in the North-West, the domain of attraction of equilibrium F is the blue saddlepath in the South-East of the diagram. For B (C) the area northeast (southwest) of the saddlepath, is the domain of attraction. For the equilibrium D the whole area between the two saddlepaths as a whole is the domain of attraction. Each basin of attraction comprises only a limited part of the state space, so that the system may flip from one basin of attraction to another one as a result of exogenous disturbance. Thus if the system was, for instance, initially on the saddle path converging to equilibrium E it may be disturbed, such that the system no longer converges to the equilibrium E, but flips into the basin of attraction of another equilibrium, e.g. C or D.

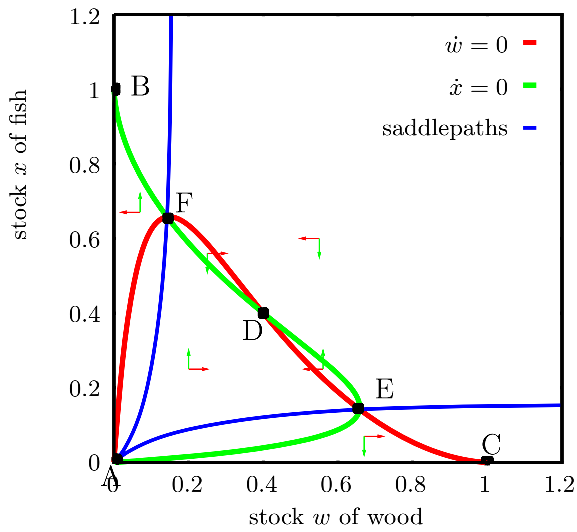

Figure 1: Phase diagram: $\dot{x} > 0$ left of the green line (< 0 right of the green line) and $\dot{w} > 0$ below the red line ($\dot{w} < 0$ above). A is an unstable equilibrium; E and F are locally saddlepoint stable equilibria; B, C and D are locally stable equilibria; the corresponding basins of attraction are the area northwest of the upper saddlepath (for B), the upper saddlepath (for F), the area in between the two saddlepath (for D), the lower saddlepath (for E), and the area southeast of the lower saddlepath (for C). Parameter values: $p_x = p_w = 0.5$, $k_x = k_w = 1$, $v_x = v_w = 1$, $\alpha = 0.6$, $\sigma = 0.4$, n = 1.

3 Analysis, Discussion and Results

The criterion for sustainability applied here is that utility resulting from the two ecosystem services shall not decrease below a specified level:

$$u(y, c, h) \geq \bar{v} \tag{8}$$

A necessary and sufficient condition for this criterion to be met is [3]:

$$\left[c^{\frac{\sigma-1}{\sigma}} + h^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}} \geq \bar{v} \tag{9}$$

In the long run this is the case for stocks of fish x and wood w for which harvest equals growth, such that condition (**??**) becomes:

$$\left[f(x)^{\frac{\sigma-1}{\sigma}} + g(w)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}} \geq \bar{v}. \tag{10}$$

We call the set of all x and w that fulfills condition (**??**) the *sustainability set* of an ecological-economic system. Its boundary is the *sustainability threshold*. To illustrate sustainable development we consider different sustainability sets corresponding to the maintenance of different levels $\bar{v}$ of utility. In particular, we consider four settings of the ecological-economic system and the sustainability sets, given different utility levels.

Case I: Resilience is necessary and sufficient for sustainable development

If the sustainability set is a subset of a basin of attraction, including a stable equilibrium (Figure 2), and if the initial state[4] is within the sustainability set, the undisturbed system will remain within the set and converge to the locally stable equilibrium. If the system is disturbed to such an extent that the system flips into another domain of attraction, it would converge to an equilibrium outside the sustainability set. In this case the resilience of the ecological-economic system in the initial state, which is within the sustainability set, is necessary and sufficient for sustainable development.

Case II: Resilience is sufficient, but not necessary for sustainable development

In the second case, the sustainability set comprises more than one locally stable equilibrium (Figure 3). Assume that the system initially is within the basin of attraction converging to equilibrium E. If the system was not resilient to an exogenous disturbance, it would flip from its initial domain of attraction into another basin of attraction and converge to a new equilibrium, for example to equilibrium D. But while the system is leaving its

[3]Condition (**??**) is necessary and sufficient for (**??**) as the consumption of the numeraire is constant, $y = (1 - \alpha)\lambda$.

[4]The initial state of the system is hereafter assigned in the figures with a big black dot.

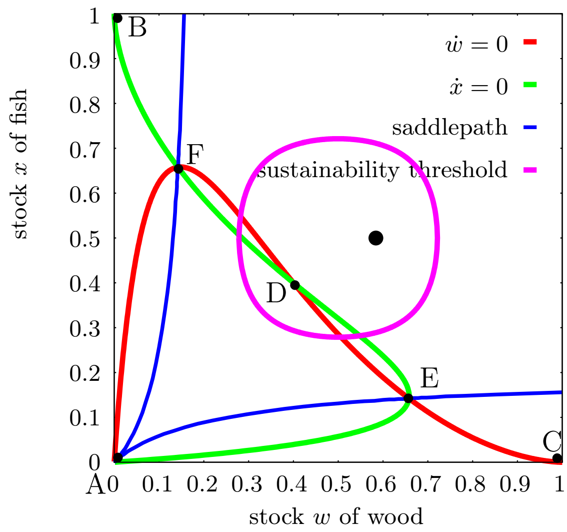

Figure 2: Phase diagram for the ecological-economic model: Resilience is necessary and sufficient.

domain of attraction it will not necessarily leave the sustainability set because equilibrium D still is within the sustainability set. Thus, in this case resilience is sufficient but not necessary for sustainable development, since in alternative domains of attraction sustainable development is also possible.

Case III: Resilience is necessary but not sufficient for sustainable development

Consider as a third case that the sustainability set is a subset of a basin of attraction, but does not include the equilibrium of that basin of attraction (Figure 4). With an initial state within the sustainability set, the system will eventually move outside the sustainability set on the path to equilibrium D. In this case resilience is necessary for sustainable development, because no other domain of attraction exists within the sustainability set. On the other hand, resilience is not sufficient for sustainable development, because no stable equilibrium is included within the sustainability set. Here, although the initial state is in a resilient basin of attraction, by its dynamics the system will move outside the sustainability set.

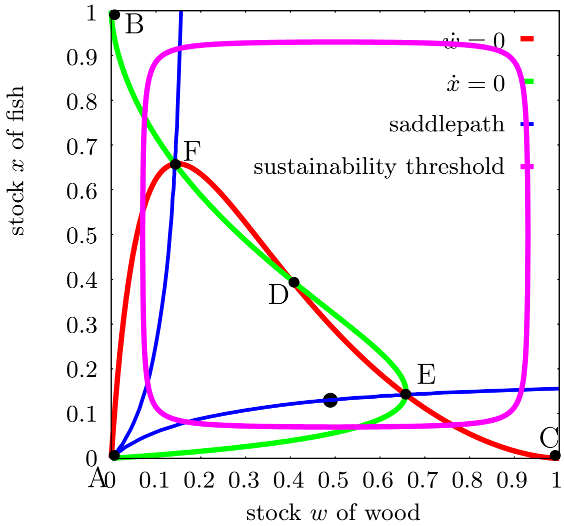

Figure 3: Phase diagram for the ecological-economic model: Resilience is sufficient, but not necessary.

Case IV: Resilience is neither necessary nor sufficient for sustainable development
In a fourth case, the system is initially in a domain of attraction that does not fulfill the sustainability requirements (e.g. point B). If the system is resilient to an exogenous disturbance it will remain within this domain of attraction and therefore outside the sustainability set. As a consequence, the resilience of the system is here neither necessary nor sufficient for sustainable development. To the contrary, resilience prevents sustainable development.

As the different cases show, the relationship between resilience and sustainable development depends on the location of the different equilibria with respect to the sustainability set. Since the fundamental distinction of the four cases discussed above is not bound on the model assumptions, the different relationships between resilience and sustainable development of ecological-economic systems found in this paper are general findings and can be applied on any ecological-economic model that features more than two equilibria.

4 Conclusion

Resilience is in the first place a purely descriptive concept: if a system does not flip into another basin of attraction due to an exogenous disturbance in a given time span, the system state is called resilient. In contrast, sustainable development is a normative concept capturing basic ideas of inter- and intragenerational justice. In this paper, we have distinguished and speci-

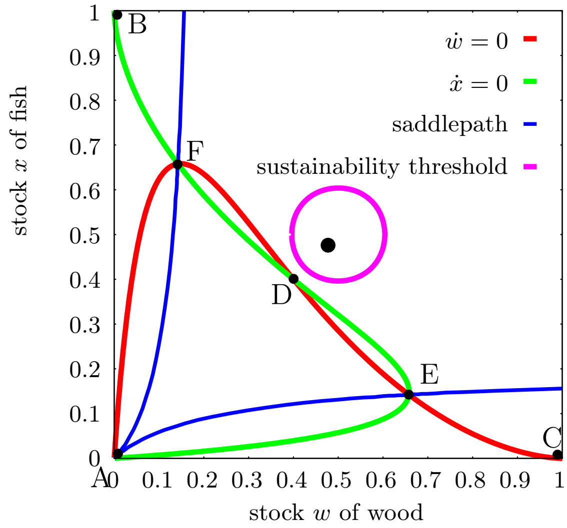

Figure 4: Phase diagram for the ecological-economic model: Resilience is necessary but not sufficient.

fied four relationships between resilience and sustainable development, using a simple model of two natural capital stocks providing ecosystem services that are complementary in the satisfaction of human needs: a) resilience of the system in a given regime is both necessary and sufficient for sustainable development, b) resilience of the system in a given regime is sufficient, but not necessary, c) resilience of the system in a given regime is necessary, but not sufficient, and d) resilience of the system in a given regime is neither necessary nor sufficient for sustainable development.

The result that there are four potential relationships between resilience and sustainable development, and the general conditions for each of those, have a much broader validity and generally hold for all ecological-economic systems with more than two basins of attraction. If a sustainability set includes more than one locally stable equilibrium, resilience is not a necessary condition for sustainable development of the ecological-economic system. On the other hand, if only one domain of attraction is located within the sustainability set, the resilience of the system within the domain of attraction is necessary for a sustainable development. Resilience prevents sustainable development if the current domain of attraction is completely outside the sustainability set. As a general conclusion from this analysis, it is most decisive for the sustainable management of ecological-economic systems to know how many domains of attractions exist within the sustainability set.

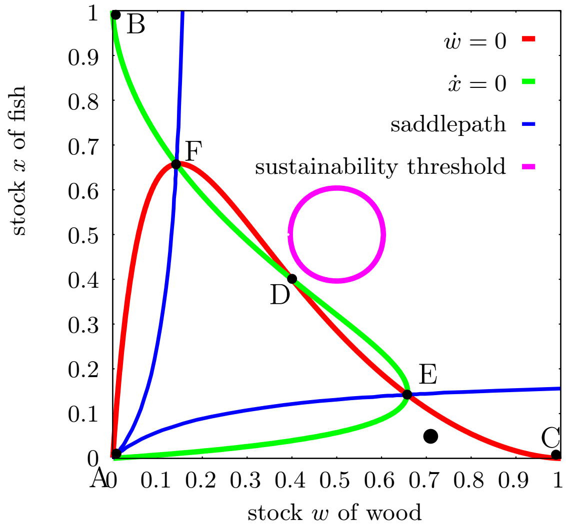

Figure 5: Phase diagram for the ecological-economic model: Resilience is neither necessary nor sufficient.

5 Appendix

Under the given assumptions the consumers, utility maximization problem is given by:

$$\max_{y,c,h} u(y,c,h) \quad \text{subject to} \quad \lambda = y + p_x c + p_w h, \tag{11}$$

with p_x and timber p_w as the market prices of fish and timber, respectively, y as the numeraire of manufactured goods and λ as the marginal product of labor.

Using utility function (5), we derive the Marshallian demand functions for fish and timber:

$$c(p_x, p_w, \lambda) = \alpha\lambda \frac{p_x^{-\sigma}}{p_x^{1-\sigma} + p_w^{1-\sigma}} \tag{12}$$

$$h(p_x, p_w, \lambda) = \alpha\lambda \frac{p_w^{-\sigma}}{p_x^{1-\sigma} + p_w^{1-\sigma}} \tag{13}$$

Furthermore:

$$y(p_x, p_w, \lambda) = (1-\alpha)\lambda \tag{14}$$

The profits of firms harvesting fish and timber are then given by:

$$\pi_x = p_x c - \lambda e_x = (p_x v_x x - \lambda) e_x \tag{15}$$

$$\pi_w = p_w h - \lambda e_w = (p_w v_w w - \lambda) e_w. \tag{16}$$

In an open-access equilibrium, which is characterized by zero profits, i.e. $\pi_x = 0$ and $\pi_w = 0$ for all firms, we thus have the following relationships between equilibrium market prices and resource stocks of fish and timber:

$$p_x = \frac{\lambda}{v_x} x^{-1} \tag{17}$$

$$p_w = \frac{\lambda}{v_w} w^{-1}. \tag{18}$$

As labor markets are perfectly competitive and each household provides one unit of labor, the total labor supply of the economy is equal to the population size. Households are either employed in the manufactured goods sector or in the resource harvesting based sector.

Inserting expressions (14) and (15) into the Marshallian demand functions (11) and (12) for fish and timber, we finally obtain the function for open access per-capita resource demands of fish and timber as functions of the respective resource stock:

$$c(x,w) = \alpha\lambda \frac{(v_x x)^{\sigma}}{(v_x x)^{\sigma-1} + (v_w w)^{\sigma-1}} \tag{19}$$

$$h(x,w) = \alpha\lambda \frac{(v_w x)^{\sigma}}{(v_x w)^{\sigma-1} + (v_w w)^{\sigma-1}}. \tag{20}$$

As a result we obtain the marked-clearing-conditions for both ecosystem services when aggregate supply equals aggregate demand which is characterized by the conditions:

$$C = m_x c^{prod} = nc(x,w) \tag{21}$$

$$H = m_w h^{prod} = nh(x,w). \tag{22}$$

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