Estimating Biological Capital: Application to Dairy Cows and Orange Orchards

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The Perpetual Inventory Method (PIM) with a geometrically-declining depreciation pattern, which is the standard approach to measuring capital in U.S. national accounts, is not appropriate for biological capital. Biological capital categories are such things as orchards and cows. They often produce little if anything in the first year, and may not reach maximum services until age 5 or 6. Because of this discrepancy, the standard PIM provides a poor measure of biological capital and its services. The objective of the present study is to provide methods to estimate wealth stocks and capital services for dairy cows and orange orchards at the national and state level for the U.S. over the period between 1960 and 2022, and present preliminary estimates for their capital stocks and services. Our approach to measuring biological capital is primarily biophysical, with foundations in capital pricing theory. The methodology proposed for animals differs from the methodology proposed for crops, and together they are representative of two common situations faced when estimating biological capital stocks: the one in which there is data on the price of new assets (i.e. the price of dairy cows sold for herd replacement); and the case where the asset is produced by the firm, with no price data on new assets (i.e. orange orchards). The estimation is performed using data from NASS (2022) and industry-relevant papers. Biophysical parameters are obtained from a series of papers, and budget sheets for crops are obtained from a variety of institutions. Our results suggest the relevance of incorporating biological capital into the national accounts. In the U.S., the average services from dairy cows have been equivalent to 1.82% of total farm sales. In Florida, the average services from orange orchards were equivalent to 5.29% of the total farm sales. The results from this paper contribute to the literature by proposing theoretically sound and feasible methods for U.S. biological capital estimation to be incorporated in national accounts as well as in productivity measurement of the sector.

Keywords: USDA, productivity, animals, crops, agriculture.

1. Introduction

It is empirically attested that the demand curve for agricultural goods tends to shift positively due to populational growth, and this change, in absence of production gains, leads to rising prices and socioeconomic consequences. This is why measuring agricultural productivity, basically the ratio of outputs to inputs, is of such great interest: productivity increases the supply of agricultural goods, and understanding its processes and drivers supports the decision-making process for policymakers.

Capital is an important input that must be appropriately considered in productivity analysis. It is not a simple concept. Although some inputs are consumed during one production process, capital provides services that are consumed along a sequence of production cycles. Thus, given that productivity change is measured as the change in outputs produced for a given set of inputs, a realistic measure of capital services used for each batch of outputs is essential to provide credible estimates of productivity growth. Measurement of capital requires both a rigorous conceptual framework and feasible empirical measurement approaches.

The standard approach to measuring capital in national accounts is not appropriate for biological capital. That standard approach, the Perpetual Inventory Method (PIM) with a geometrically-declining depreciation pattern, assumes that once an asset is placed in service, the flow of services follows a geometric decay pattern through its lifetime. This results in an asset price that also declines geometrically through its lifetime. The convenient result is a simple method of tracking the market value of all capital items: just add investments to stock this year and reduce its value by a given percentage (the depreciation rate) each year thereafter. But biological capital categories are such things as orchards, cows, or vineyards. They often produce little if anything in the first year, and may not reach maximum services until age 5 or 6. The standard PIM approach is for assets whose maximum service flow is the first year, declining thereafter. Because of this discrepancy, the standard PIM provides a poor measure of biological capital and its services.

Theory and empirical methods for biological capital have been the object of recent studies in the literature for capital measurement. According to United Nations. et al. (2009), biological resources include non-cultivated and cultivated assets, the last one being defined as those being used for multiple years to produce other goods or services, under direct control, responsibility, and management of institutional units. In this study, we are particularly interested in modeling cultivated biological resources and will use the terms “cultivated assets”, “living assets” and biological capital as their synonyms.

As discussed by (Diewert, 2005), the role of cultivated assets has been increasing over time. Thus, the System of National Accounts 2008 (United Nations. et al., 2009) as well as the Shumway et al. (2014) USDA report recommend that it should be tracked as capital. However, when accounting for living assets, data availability as well as the complex dynamics associated with their flow of services present challenges that have been the subject of different studies.

The objective of the present study is to provide a methodology theoretically robust and empirically feasible to estimate biological capital stocks at the national and state level for the US over the period between 1960 and 2022, and estimate the wealth stock and capital services for dairy cows and orange orchards.

2. Methodology

2.1. Theoretical basis for biological capital estimation

According to Soloveichik (2019), while some European Union countries have tracked cultivated assets as capital in their national accounts, neither the U.S. Bureau of Economic Analysis (BEA), the U.S. Department of Agriculture's (USDA) Economic Research Service, nor the U.S. Bureau of Labor Statistics (BLS) currently tracks cultivated assets consistently. Long-living animals are treated by BEA as inventories and this has implications for the estimations of Gross Domestic Product as well as total factor productivity.

As mentioned above, the standard approach to estimating capital stock is the Perpetual Inventory Method, whose foundations are the papers of Solow (1955), Fisher (1965), and Hall (1968). The basic principle of capital aggregation introduced by Solow (1955) is that a given output Y can be produced through a production function $f(.)$ whose inputs are the services (C_1 and C_2) from two categories of capital, plus other inputs such as labor L. If this function is allowed to be collapsed to a new function $F(.)$ whose arguments are an aggregate J of services from the existing types of capital, and the other inputs L, then there is an aggregate measure of capital. Mathematically, Solow (1955) represents it as

$$Y = f(L, C_1, C_2) \equiv F(L, J) \tag{1}$$

$$J \equiv \phi(C_1, C_2) \tag{2}$$

Where ϕ is an aggregation function for capital. By calculating the marginal rate of substitution between C_1 and C_2 from equation 1, Solow (1955) obtains

$$\frac{MPP_1}{MPP_2} = \frac{df/dC_1}{df/dC_2} \equiv \frac{\frac{dF\,d\phi}{dJ\,dC_1}}{\frac{dF\,d\phi}{dJ\,dC_2}} \equiv \frac{d\phi/dC_1}{d\phi/dC_2} \tag{3}$$

Equation (3) is a necessary and sufficient condition[1] for capital aggregation: the marginal rate of substitution between two kinds of capital must be independent of the amounts of other inputs.

If one considers (1) as a vintage model of production[2], we can assume C_1 is the service from a biological asset from vintage v_1, and C_2 is the service from the same kind of biological asset but from a different vintage v_2. In such a case, Hall (1968) shows that assuming vintage production functions including capital and labor, based on (1) and (2), a

[1] As discussed by Solow (1955), the condition stated in 3 is necessary for the collapsibility of the production function 1, and then for the existence of an aggregate capital; and the theorem of Leontief shows that 3 is also a sufficient condition for such aggregation.

[2] In a vintage production model we assume assets produced in different years (created in different vintages) are combined with other inputs to produce a given output.

necessary and sufficient condition for the existence of J is that the vintage production function has the form

$$f(v, I(v), L(v)) = F(z(v)I(v), L(v)) \tag{4}$$

Where v is the vintage of the capital; $I(v)$ is the investment made on capital of vintage v; $L(v)$ is labor allocated to the vintage v capital; and *z(v)* measures all differences in efficiency distinguishing assets from different vintages, which includes technical change and deterioration. Finally, Hall (1968) also shows that, under profit maximization and perfect competition, from a theorem of Leontief, (4) implies a rental price function $c(v)$

$$c(v) = z(v)G(w) \tag{5}$$

Where $G(w)$ is a function of wage. This means that the ratio of the rents of assets from different vintages in the same period t should be independent of the price of other inputs.

Expression (5) provides a theoretical basis for the Perpetual Inventory Method, which is that capital services can be measured as the weighted sum of past investments, where $z(v)$ gives the weights. Another relevant conclusion is that the ratio of rental rates in a given period is equivalent to $z(v)$, which is empirically convenient when $z(v)$ is not directly observable but prices are.

Currently, the Perpetual Inventory Method has been adopted for biological capital estimates, but some researchers have also proposed strategies for capital stock estimation through the specification of $z(v)$. Ball & Harper (1990) depart from Hall's (1968) definition of vintage coefficients to estimate $z(v)$ for dairy and beef cows based on biophysical data. Through this strategy, the authors can use data on survival, age-efficiency profile, and genetics improvement (embodied technical change) to weight capital units. The resulting estimate is what the authors call "real capital input", given by[3]

$$J(t) = \sum_{\tau=0}^{L} h(\tau)b(t-\tau, t_0)N(t, \tau) \tag{6}$$

Where $J(t)$ is the real capital input at time t, which is equivalent to the capital services; $h(\tau)$ is the efficiency of a τ-years old capital unit relative to age 1; $b(t-\tau, t_0)$ is the embodied technical change of a τ-years old capital unit taking period t_0 as the basis, which is measured as the ratio between the expected marginal physical products under the same management practices for a cow from vintage $t-\tau$ and a cow of the same age from vintage t_0; $N(t, \tau)$ is the number of assets, at time t, with age τ. According to Ball & Harper (1990), $J(t)$ is a representation of the inherent capacity of the animals in the herd to produce output (i.e., milk), and it is represented in terms of equivalent units of new cows from the period t_0.

Ball & Harper (1990) also propose a measure of wealth capital stock for biological capital, which is given by the market value of the assets in operation in a given year. It is calculated through the multiplication of the elements of a vintage counting matrix by elements of a price matrix. The price structure prevailing in each year they estimate from data on prices of new assets per year, based on price assumptions used in neoclassical

[3] We specify the technical change index as being $b(t-\tau, t_0)$ instead of $b(t-\tau)$ as specified by Ball & Harper (1990) because the period used as the basis for such index plays a role when analyzing ratio of expected marginal physical product.

production theory, and an interest rate. The authors do not describe it in detail, however, the model used to generate the price structure. Thus, it is not possible to do a critical analysis of the strategy proposed by them.

Pardey et al. (2006) also estimate $z(v)$ based on data on the prices of new assets. Under the assumption of geometric depreciation, age-price and age-efficiency profiles follow geometric progressions, which allow for the use of the ratio of prices to weigh assets from different ages and types. Then, the capital services proposed by Pardey et al. (2006) are estimated as

$$S_{1,t} = \sum_{i=1}^{N} \sum_{k=1}^{L} \left[\frac{W_{1,i}}{W_{1,1}}\right] (1-\delta)^{k-1} q_{k,1,t} \quad (7)$$

Where $S_{1,t}$ is the aggregated capital stock in new equivalent units of capital type 1, what is equivalent to the capital services J(t); $W_{k,i}$ is the purchase price of k-year-old capital type i; δ is the geometric rate of depreciation; $q_{k,i}$ is the number of k-years old units of capital type i. In equation (7), the term $(1-\delta)^{k-1}$ is related to the age-efficiency effect, while the ratio of prices $\left[\frac{W_{1,i}}{W_{1,1}}\right]$ is related to differences in productivity across types of assets[4].

The methodology employed to estimate biological capital stocks in this paper is described in this topic and consists of two strategies. When there is data on price of new assets, which is the case for dairy cows, we define a method to estimate the rent and price per age of animals using pricing assets theory and a set of parameters. When data on price of new assets is not available, which is the case of orange orchards, we estimate rent and price of the asset per age using enterprise budgets.

Because living assets provide inputs for multiple periods, capital services from biological capital stocks follow a logic of stock and flow. As mentioned before, the most used method for capital stock estimation is the Perpetual Inventory Method (PIM), which consists of an investment series and a depreciation rate.

Ball et al. (2015), Acquaye et al. (2003), and Soloveichik (2021) use the following concepts, rather than investment and depreciation, to estimate biological capital:

- Service life: is represented through a survival function for biological capital with maximum life L (Ball et al., 2015).

- Age-efficiency profile is a ratio between the marginal productivity at various ages relative to the first-year marginal productivity.

- Despite the apparent simplicity of these concepts, several issues rise due to both: differences in the service's dynamics of biological capital, and data scarcity.

[4] Pardey et al. (2006) assume that different types of assets present identical service profile (depreciation rate and service life), except by the level of marginal product. Then, the ratio of the expected marginal product of 2 types of asset in a given age is assumed to be constant. Under the assumption of a common service flow profile, the ratio of prices can be used as weight to aggregate assets of same age in equivalent units of the type of asset whose price is used as denominator.

While the expected marginal productivity for physical capital monotonically declines along the aging-productivity profile, living assets usually reach maximum productivity later than the first year. The marginal productivity of a dairy cow, for example, is 0 until it calves for the first time. For an orange plantation, production starts just after 2-3 years from planting and the tree is considered an adult (full productivity potential) 6 years after being planted. This dynamic of service flow results in a non-monotonic age-efficiency profile which can be very different from the one represented through the broadly adopted geometric function.

Another issue in estimating the aggregate stock and flow of services using this approach is that it is necessary to know the vintage composition of the assets in service each year, and such data usually are not directly available for biological capital. The lifespan for biological assets is given by the interaction between the asset itself, the environment, and economic decisions.

A measure like the one proposed in the present study includes three components: a matrix of age-rent profiles (rents per age and year), a matrix of age-price profiles (prices per age and year), and a vintage counting matrix (number of animals per age and year). Multiplying elements of the vintage counting matrix by corresponding elements of the matrix of age-rent profiles, a matrix of capital services per year and age is obtained. Adding up the services from different ages for each year, plus the revenues from slaughtered animals, an estimate of capital services per year is obtained. Similar multiplication of the elements of the vintage counting matrix by the matrix of age-price profiles results in a matrix of wealth capital stock per year, disaggregated by age. Adding up the stocks from different ages for each year, estimates of capital stock per year are obtained. The difference between capital stocks in two consecutive periods minus investment gives the consumption of fixed capital (or depreciation) (Schreyer, 2009).

The simple approach we use is to assume that the departure of biological assets follows a survival function, as done by (Ball & Harper, 1990). Although this ignores the economic theory of asset replacement (i.e., Perrin, 1972), it includes the ecological dimension of survival, which leads to what appears to be realistic estimates of the vintage composition and, consequently, of the capital stock.

2.2. Methods for biological capital estimates for dairy cows in the US: capital measurement using data on price of new assets

2.2.1. Counting vintages

The vintage counting is that of Ball and Harper with few changes. The first version can be found in Ball & Harper (1990), and an updated version is in Ball et al. (2015). The departing point is to define a matrix N(t,τ) of the number of assets (cows) in service by age τ (column) each year t (row), given by:

$$N(t,\tau) = I(t-\tau+1)w(\tau) \tag{8}$$

where I$(t-\tau)$) is the number of replacement cows (investments) placed in service in yeat t- τ and w(τ) is the cumulative survival function of the asset (% of assets left at age τ). Note that $N(t,1)$ is the investment at time t, I(t).

Asset counting by vintage is made through an iterative process. Assuming an initial vintage composition[5], a preliminary estimate of assets surviving in each year is calculated as

$$S^{*}(t+1)=\sum_{\tau=1}^{L} N(t,\tau).\left(\frac{w(\tau+1)}{w(\tau)}\right) \tag{9}$$

in which L is the service life, and $S^{*}(t+1)$ is a preliminary estimate of the number of cows surviving from period t to $t+1$ given the survival function $w(\tau)$. An adjustment ratio, the ratio of the observed surviving animals to the estimated survival animals, was calculated as being

$$R(t+1)=\frac{N(t+1)-I(t+1)}{S^{*}(t+1)} \tag{10}$$

where $I(t+1)$ is the number of heifers kept for milk replacement in time $t+1$. This adjustment ratio is used to create final estimates of surviving animals of every age for year t, conforming to the observed totals

$$N(t+1,\tau+1)=N(t,\tau).\left(\frac{w(\tau+1)}{w(\tau)}\right).R(t+1) \quad \text{for } \tau<L \tag{11}$$

$$N(t,L)=0 \quad \text{for } \tau=L$$

In (11), $N(t+1,\tau+1)$ is the final estimate for the number of cows surviving from period t to $t+1$, for animals of vintage τ to $\tau+1$. The adjustment ratio $R(t+1)$ is applied to correct potential errors in the estimated survival due to the imprecision of the assumed survival function.

The final number of slaughtered cows is given as

$$B(t+1)=\{S(t)-[S(t+1)-I(t+1)]\}(1-dl) \tag{12}$$

Where $B(t+1)$ is the estimated number of cows slaughtered; S(t) is the total number of cows, $[S(t+1)-I(t+1)]$ gives the number of cows surviving from period t to $t+1$, and dl is the average rate of death loss, which we estimate as 2.11%[6].

[5] According to Ball & Harper (1990)Ball & Harper (1990) the effect of the initial vintage composition disappears over time, and some simulations we developed corroborate this.

[6] It is the average death loss for cattle, excluding calves, in the U.S. for the period 1945-2021, estimated from numbers available on NASS (2023)NASS (2023). This rate has been stable during the whole period, presenting very small standard deviation (0.0015).

2.2.2. *Pricing assets: Using equilibrium in the new asset market to generate annual age-price profiles*

2.2.2.1. Estimating the rent for new assets

The objective of this study is to estimate biological capital stock. OECD (2009) defines total net capital stock as the market value of assets.

The strategy adopted in the present study follows the asset-counting strategy above and pricing theory as described by Hall (1968). We measure the value of assets by age using the following notation:

t: current period;

r: the discount rate

v: vintage year of an asset, the year when the asset was placed into service.

$\tau = t$–v+1: the age of an asset

L: lifespan of the asset. It is the maximum number of years along which the asset can provide a flow of services;

$R(t)$: the salvage value in period t of the asset at any age;

$w(\tau)$: the estimated fraction of assets that will be in the productive stock at age τ; the survival function;

$y(t, v)$: the quantity of services in period t of a vintage v asset;

$p(t)$: the price of a unit of service of an asset in year t;

$c(t, v) = p(t)y(t, v)$: The "rent" (value marginal product) that a vintage v asset earns at age τ (i.e., in year t = v+τ+1);

$e(\tau)$: the "age-efficiency profile"; the productivity of an asset of age τ relative to age 1. i.e. y(τ,v)/y(1,v) for all v;

$b(v, t)$: an index of technological change: productivity of a vintage v asset relative to a vintage t asset, i.e. y(v+ τ,v)/y(t+τ,t) for all τ;

$P(t, v)$: the "age-price" profile; the market value in period t of a vintage v asset.

Because market prices of assets by age are not available, we estimate the age-price profiles based on the perfect market equilibrium assumption that at time t the market price P(t,v) equals the expected net present value of future rent and salvage earnings. This equilibrium condition in its general form is

$$P(t, v) = E_t[PV\ of\ future\ earnings \mid w(.)] = E_t\left[\sum_{x=t}^{t+L} c(x, v)e(x - v + 1)(1 + r)^{(t-x-1)} \mid w(x - v + 1) \right] + E_t\left[\sum_{x=t}^{t+L} R_S(x)(1 + r)^{(t-x-1)} \mid \left(1 - w(x - v + 1)\right) \right] \quad (13)$$

It is worth noting that equation (13) has t and v as arguments, which means that prices of living assets in a given year would differ across vintages. This vintage effect is explained by differences in services provided and differences in the expected survival. Another relevant aspect of this expression is that we discount rents of year t, which implies that the price $P(t,v)$ is defined as being the price for the beginning of the year t for an asset from vintage v.

From Hall (1968), the existence of a capital aggregate implies that rent in the period t of a living asset whose vintage is v is given by

$$c(t,v) = y(t,v)p(t) \tag{14}$$

Equation (14) expresses the rental rate $c(.)$ as a function of the marginal physical product $y(.)$ and the service price $p(t)$. Marginal product $y(t,v)$ varies over time because it may be affected by non-embodied technical change; it changes with $(t-v+1)$ because of changes in productivity along the service life (age-efficiency effect); it is also a function of v because of changes in genetic characteristics over time (vintage effect). $p(t)$ changes over time because it is a function of many other price variables.

We can observe replacement dairy cow prices when they are placed in service, *P(t,t)*, and their salvage value, $R_s(t)$ which allows us to solve equation (13) for $c(t,t)$, the first-year rent expected to be earned by an asset of vintage *t*, as described next. Given this estimate, we use equation (14) and the age-efficiency profile *e(t-v+1)* to estimate the age-price profile as the cows age.

To utilize equation (13) to represent producers' investment decisions, we specify expectations as $E_t[p(x)] = p^e(t)$, and $R_S^e(x) = R_s(t)$ for all x>t.

$$P(t,t) = \sum_{x=t}^{t+L} c(t,t)e(x-t+1)(1+r)^{(t-x-1)}w(x-t+1) + \sum_{x=t}^{t+L} R_S^e(t)(1+r)^{t-x-1}[w(x-t+1)-w(x-t+2)] \tag{15}$$

Solving for $c(t,t)$

$$c(t,t) = \frac{P(t,t) - R_S^e(t)\sum_{X=t}^{t+L}(1+r)^{t-x-1}[w(x-t+1)-w(x-t+2)]}{\sum_{X=t}^{t+L} e(x-t)(1+r)^{(t-x-1)}\, w(x-t)} \tag{16}$$

, or

$$c(t,t) = \frac{P(t,t) - R_S^e(t)k_S(v,r)}{k_c(v,r)} ,$$

where $k_s(v,r) = \sum_{X=t}^{t+L}(1+r)^{x-t-1}[w(x-t+1)-w(x-t+2)]$, and

$$k_c(v,r) = \sum_{X=t}^{t+L} e(x-t)(1+r)^{(t-x-1)}\, w(x-t+1).$$

For every year we calculate $c(t,t)$ using data on the observed price of replacement dairy cows P(t,t), observed salvage value $R_s(t)$, assumed survival function and age-efficiency profile. Given the solution (16) for the first-year rent of a new asset in each period t, subsequent prices of the vintage t asset can be calculated as it ages as $\big(P(t+k,t)\big)$ using the information described above and expected service prices. This strategy is explained in the next topic.

2.2.2.2. Pricing assets of different vintages based on the rental rate of new assets and commodity prices (the UNL approach)

As mentioned above, we use equation (16) to estimate the rental rate of a new asset, $c(t,t)$, in each period t. From expression (14) we have that $c(t,t) = y(t,t)p(t)$, which means that differences in the estimated rental rate between two periods $\left(c(t_1,t_1) \neq c(t_2,t_2)\right)$ are related to either difference in the productivity of a new asset $y(t_1,t_1) \neq y(t_2,t_2)$ or to the difference in service prices $\left(p(t_1) \neq p(t_2)\right)$. In the UNL approach, we use $c(t,t)$ and equation (15) to price a vintage t asset as it ages, $P(t+1,t)$, $P(t+2,t), \dots, P(t+L,t)$, where L is the service life of such an asset.

Now consider the effect of commodity prices p(x) on rent in period x. In the absence of non-embodied technical change, the marginal product of a vintage v asset changes with age according to the age-efficiency profile, i.e. y(x,v) = y(v,v)e(x-v). Then from equation (14)

$$\frac{c(x,v)}{c(v,v)} = \frac{p(x)y(x,v)}{p(v)y(v,v)} = \frac{p(x)}{p(v)} e(x-v+1)\text{ , or}$$

$$c(x,v) = \frac{p(x)}{p(v)} e(x-v+1)c(v,v) \quad , \tag{17}$$

Inserting this into the present value expression (13) we obtain the result to be used to track asset prices through time:

$$P(t,v) = \sum_{x=t}^{v+L} \frac{p^e(x)}{p(v)} e(x-v+1)c(v,v)(1+r)^{(t-x-1)} \frac{w(x-v+1)}{w(t-v+1)} + \sum_{x=t}^{v+L} R_S^e(t)(1+r)^{t-x-1} \frac{[w(x-v+1)-w(x-v+2)]}{w(t-v+1)} \quad \text{or}$$

$$P(t,v) = \frac{p^e(t)}{p(v)} \frac{c(v,v)}{w(t-v+1)} \sum_{x=t}^{v+L} \frac{e(x-v+1)w(x-v+1)}{(1+r)^{x-t-1}} + \frac{R_S^e(t)}{w(t-v+1)} \sum_{x=t}^{v+L} \frac{[w(x-v+1)-w(x-v+2)]}{(1+r)^{x-t-1}} \tag{18}$$

Thus, expression (18) is used to price a vintage v asset while it ages. The underlying intuition behind this expression is that as the asset ages with time t we adjust the initial rental rate of this asset $\left(c(v,v)\right)$ based on the change in the price of services from the vintage v to the current period t, as well as change due to the age-productivity profile.

An issue remaining using (18) is to specify expected service prices at different future periods ($p^e(x)/p(v)$). In the Appendix there are two examples we used to look at this issue, both suggesting that a simple ratio of output price to input price is not a satisfactory solution.

We can think of rent, c(t,t), as the initial profit from the use of this asset. Interpreting c(t,t) as a profit function, this rent is homogeneous of degree one in prices, and, assuming that the relative prices of dairy outputs and inputs do not change considerably over time, the ratio of output prices can be used as a proxy for the ratio of service prices.

Using equations (17) and (18), one obtains the rent and prices of assets, per age, for each year. Multiplying the elements of the vintage counting matrix N(t,τ) defined in (11), by the elements of the matrix of rents per age (row) and year (column), a matrix of capital services is obtained per year (row) and age (column). Adding up the services from different ages for each year, plus the revenues from slaughtered animals, an estimate of capital services per year is obtained.

Multiplying the elements of the vintage counting matrix N(t,τ) defined in (11) by the corresponding elements of the matrix of prices per age (row) and year (column), a matrix of wealth capital stock per year (row) disaggregated by age (column) is obtained. Adding up the stocks from different ages for each year, an estimate of capital stocks per year is obtained.

2.3. Methods for biological capital estimation for orange orchards in Florida and California: capital measurement using budget sheets

For dairy cows, biological capital can be estimated under reasonable assumptions when there are data available on the price of new assets, the total number of assets, and age-efficiency and survival parameters. This is not the case for permanent crops such as orchards and pastures.

A vintage counting model, and therefore data on the total number of trees (acres) and survival parameters are still needed to estimate a vintage counting matrix for orchards. In the absence of data on the price of new assets, budget studies can be used to estimate age-rent and age-price profiles. The age-rent profile can be approximated as the age-net revenue profile, and the age-price profile can be approximated as the age-net present value profile.

When estimating capital stocks and services for permanent crops, the main challenge is that budget or cost analyses are not available for every year, variety, production system, and location in the U.S. Therefore, it is necessary to define representative budgets based on the studies available in the literature.

In the present analysis, we estimate the market value or “price” of an acre of orchard in a given year by calculating the present value of estimated future earnings over the remaining lifetime of the orchard.

The age, or vintage, composition of the state’s orchards is tracked through time using data on bearing acreage, and assuming zero mortality until the end of the lifespan, because the budgets account for the maintenance cost of replacing dead trees. A key assumption behind our valuation strategy is that per-acre net revenue is homogenous of degree one in yield (costs and revenues change in the same proportion as yield changes) and also in output price (as a profit function is).

2.3.1. Lifespan and age-productivity profile for orchards in Florida and California

Citrus greening (HLB) has impacted orange production. It was first found in Florida in 2005, and in 2015 was already spread in every county across the state (Florida Department of Citrus, 2018). As a consequence of this disease, the age-efficiency profile of orange groves (lifetime path of yields per acre by age of orchard) was impacted. A comparison of age-yield profiles before 2005 (Spreen et al., 2003) and after the disease was completely spread (Singerman et al., 2018) shows a considerable decrease in yield due to HLB. Besides the impact on yield, Singerman et al. (2018) assert that the average lifespan of orange orchards decreased from 30 to 20 years in Florida due to the disease.

To incorporate those effects into the estimates of age-price profiles, we use the age-productivity profiles of Spreen et al. (2003) as being representative of orange production before HLB, and the one adopted by Singerman et al. (2018) after HLB infection. We assume that the disease spread linearly between 2005 and 2015 and that it reduced the yield of infected orchards younger than 20 years old and killed the infected orchards older than 20.

In Figure *1*. Age-productivity profile of oranges (all varieties) in FL. A box is equivalent to 55 lbs of orange. we chart the estimated average age-productivity profile for Florida orchards between 2005 and 2015. For orchards with ages up to 20 years, it is a weighted average of the yield before and the yield after the period over which the infection spread, where the weights are the percentage of bearing acreage noninfected and infected, respectively (Figure 4). This assumes that HLB infected orchards of different ages by the same intensity.

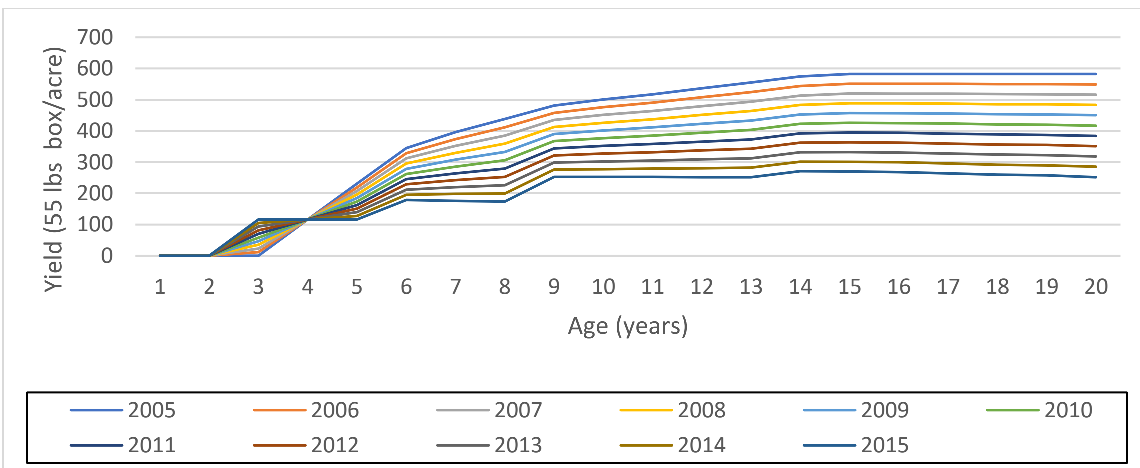


Figure 1. Age-productivity profile of oranges (all varieties) in FL. A box is equivalent to 55 lbs of orange.

Source: Own elaboration based on Spreen et al. (2003) and Singerman et al. (2018).

As mentioned before, HLB was first discovered in California in 2012, but it has been aggressively combated through a voluntary area-wide pest management program (Li et al., 2020), and the production has not shown signs of impact due to this disease. Budget sheets from 1964 and 2021 from the University of California-Davis were used to estimate representative age-rent and age-price profiles for Californian orchards, and the assumptions adopted in those cost studies show no evidence that impacts of citrus greening should be incorporated for this state. The age-productivity profiles obtained from UCDavis (2023) are presented in (Figure *2*), and the lifespan is assumed to be 30 years for the whole period.

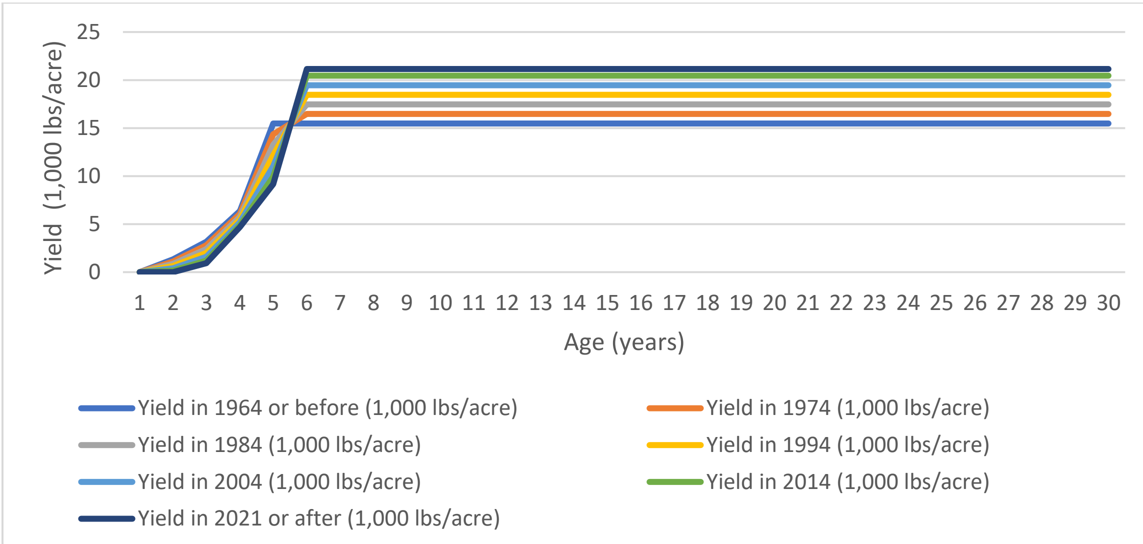


Figure 2. Age-productivity profile of oranges (all varieties) in FL. A box is equivalent to 55 lbs of orange

Another relevant disease affecting citrus production in the U.S., more specifically in Florida, is the Citrus Canker, caused by a highly contagious bacteria that came originally from Asia (Luckstead & Devadoss, 2021). It was first found in the U.S. in 1910 (Berger, 1914). The disease was considered eradicated in Florida in 1933, but new outbreaks happened in 1986 and 1995 (Gochez et al., 2020). Removal of trees was the main strategy adopted against the Citrus Canker, but in 2006 the USDA abandoned the tree eradication program (Centner & Ferreira, 2012).

Given that the main strategy adopted against Citrus Cranker was tree removal, we do not incorporate explicitly the impact of this disease on the productivity of trees. However, tree removal is implicitly accounted for in the vintage counting as decreases in bearing acreage.

2.3.2. Vintage counting

Construction of the orange orchard capital account requires an estimate of the number of acres by age of the orchard (we refer to this as vintage counting). We did not find any consistent data on the number of acres planted by year, so we estimated this investment as the change in total bearing acreage minus the number of acres of maximum age in the previous year (which we assumed to be discarded).

To construct orchard acreages by vintage, we started the series in the year 1931, assuming a uniform distribution over age. For subsequent years we advanced the ages of these acreages by one year (with no loss in tree numbers with age because the budgets include the cost of replacing trees as needed). For periods of negative investment, it was assumed that disinvestment was proportional across ages, which is consistent with the idea that big reductions in bearing acreage happened due to natural disasters and diseases that affected orange orchards in the same intensity independent of their age.

2.3.3. *Estimating rent and price of orange orchards for Florida*

In the present analysis, capital services are interpreted as the revenue net of variable costs for the orchard. There are no budgets available for every year during the period of analysis, therefore it is necessary to define a strategy to estimate representative budgets per year based on the scarce information available. We adjust the per-acre net revenue profile estimated by Singerman et al. (2018) for orange production in Florida in 2018 using differences through time in yields and prices. We define the net revenue that a vintage v asset earns at period t as $c(t, v)$:

$$c(t, v) = p(t)y(t, v) \tag{19}$$

Where $y(t, v)$ is the quantity of services in period *t* of a vintage v asset; and *p(t)* is the price of a unit of capital service in year *t*. From Singerman et al. (2018) we have data on $c(2018, v)$, where $2018 - v \leq 20$. We assume that vintage effects on the cost structure of oranges are not significant and that changes in the productivity profile happen due to exogenous shocks such as the incidence of greening citrus. The rent of an asset age τ in period t' $\left(c(t', t' - \tau)\right)$ in current value can be estimated based on the rent of an asset τ in period t $\left(c(t, t - \tau)\right)$:

$$\frac{c(t', t'-\tau)}{c(t, t-\tau)} = \frac{p(t')}{p(t)} \frac{y(t', t'-\tau)}{y(t, t-\tau)} \rightarrow$$

$$c(t', t' - \tau) = \frac{p(t')}{p(t)} \frac{y(t', t'-\tau)}{y(t, t-\tau)} c(t, t - \tau) \tag{20}$$

Interpreting $c(t, t - \tau)$ as a profit function, this rent is homogeneous of degree one in prices, and, assuming that the relative prices of oranges and inputs do not change considerably over time, the ratio of orange prices across time can be used as a proxy for the ratio of service prices. Having data on the yields over time, the ratio $\frac{y(t', t'-\tau)}{y(t, t-\tau)}$ can be proxied as the ratio of yields in t' and t. This provides age-net revenue profiles for orchards of various ages for each year.

The age net revenue profiles estimated through the methodology described above can be interpreted as the capital services profile. For every year t, the capital services can be estimated by multiplying the vector of bearing acreage per age by the vector of rents (capital service) per age.

Finally, the price profile per year can be estimated as the discounted sum of future rents:

$$P(t, v) = \sum_{x=t}^{v+L} c(x, v)(1 + r)^{(t-x-1)} \tag{21}$$

Where r is the discount rate; and $c(x, v)$ is estimated by Equation (20) for every year and vintage of our series based on Singerman's (2018) budget, data on the price of oranges per year, and the age-productivity profiles (yields) presented in Figure 2. Equation (21) incorporates the assumption of 0 mortality, which is consistent with the budget of Singerman et al. (2018) that incorporates costs related to the replacement of trees.

The approach adopted for California is similar to the one adopted for Florida, except that for California we have publications of cost studies that allow us to estimate representative budgets incorporating changes in the cost structure of orange production. This is done in the present analysis by using two budgets from UCDavis (2023), one from 1964 and another one for 2021. Their respective age-rent profiles were deflated to 2021 values, and the budgets for orchards planted in all of the other years between 1960 and 2022 were obtained through linear interpolation. Finally, a matrix of age-rent profiles is obtained through this method by inflating the estimated rents to current values using a price index of oranges in California.

Finally, for Florida and California, the wealth capital stock is obtained by multiplying the elements of the vintage counting matrix by the matrix of age-price profiles. The capital services are estimated by multiplying the vintage counting matrix by the matrix of age-revenue profiles.

2.4. Data

We assume a rate of death loss of 2.11%, which is the average rate of death loss observed for cattle (excluding calves) during the period 1945-2021 (NASS, 2023) (Figure 3). It has been stable over the period.

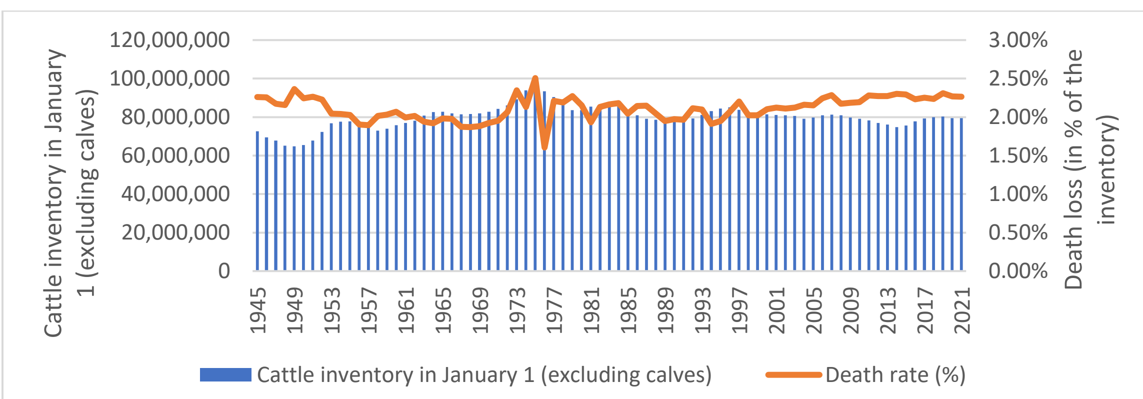


Figure 3. Death loss and cattle inventory.

Source: own elaboration using data from NASS (2023).

To apply formula (18) to price assets, it is necessary to have data on expected salvage value. For dairy cows, the salvage value is the price received by producers for dairy cows sold for slaughter. NASS does not have that price, but it has data available on: price per cwt (live weight) for all cows sold for slaughter; dressed weight of cows and cattle GE 500 lbs; and live weight for cattle GE 500 lbs. Live weight for cows is not available from NASS, so we construct our estimate of salvage value per cow as follows.

We assume that the ratio of live weight between cows and cattle GE 500 lbs is equal to the ratio between the dressed weight of both classes of animals. This provides our final estimates for the live weight of culled dairy cows, which varies from 777 to 1,070 lbs, with mean 901 lbs.

A summary of the data and parameters used to estimate biological capital stocks and services for dairy cows is shown in Table 1.

Table 1. Variables that are included in the calculation of the national-level capital stock of dairy cows

Variable	**Data**	**Average (1960-2021)**	**Minimum**	**Maximum**
$S(t)$ = total herd	Inventory of dairy cows, in million head (NASS, 2023)	11.12	8.99	19.53
$S^*(t+1)$ = slaughtered cows	Slaughtered dairy cows, in million head (NASS, 2023)	4.19	3.71	5.32
Heifers kept for milk	Heifers 500 pounds and over kept for milk cow replacements, in heads (NASS, 2023)	4.23	3.44	5.08
$p_Y(t)$ = price of capital services[7]	Dairy product price - index for the prices received (2010 basis) (NASS, 2023)	0.947	0.74	1.48
$P(v,v)$ = Price of a new asset, per head	Price paid for milk cows for dairy replacement only (in $/head) (NASS, 2023).	$1,017	$209	$1990
$R_S(t)$ = Salvage value, per head	Estimated based on the estimated live weight of culled cows and the price per cwt of cows sold for slaughter	$398	$99	$1,126
$e(x-v+1)$ = Age-efficiency profile	Data for age-efficiency pattern of dairy cows (Norman et al., 1974) (age 1, age 2, age 3, age 4, age 5, age 6, age 7)	1, 1.121, 1.218, 1.271, 1.293, 1.292, 1.282	-	-
$w(\tau)$ = survival function	% of cows surviving from the first lactation to age τ (Nieuwhof et al., 1989) (age 1, age 2, age 3, age 4, age 5, age 6, age 7)	1, 0.782, 0.45, 0.183, 0.05, 0.008, 0.001	-	-
r = interest rate	The discount factor for the present value of future services.	0.04	-	-
L = service life	Maximum service life assumed for a dairy cow (Nieuwhof et al., 1989)	7	-	-

For orange orchards, data on bearing acreage and orange prices for the period between 1960 and 2021 was obtained from the Citrus Fruits report (USDA, 2023).

[7] Assuming that the change in service prices is directly proportional to the change in output prices, the ratio of dairy price indexes is equivalent to the ratio of service prices and can be used in equations (11) and (12).

2.5. Price expectations

The pricing theory described above approximates the price of animals by the expected value of the flow of services provided over their remaining service life. Thus, it becomes necessary to construct price expectations. The literature has used ARIMA predictions as an estimate of rational expectations. Dupont (1993), and Nerlove (1979) examine ARIMA processes and show that they have the properties of rational expectations as defined by Muth (1961). Through experimental analysis, Nelson and Nelson & Bessler (1992) found evidence that forecasts from an ARIMA model represented satisfactorily the aggregate expectations for relatively simple series such as the ones generated by autoregressive processes of first or second-order.

Alternative methods to estimate price expectations have been discussed more recently. The Hodrick-Prescott (HP) filter, a strategy to remove short-term fluctuations from time series, has been used in OECD models to generate proxies for inflation expectations (Orr et al, 1995; Martins & Scarpetta, 1999). Asha et al. (2002) analyze the Hodrick-Prescott (HP) filter as a strategy to obtain a proxy for expected prices, and the authors concluded that the HP series is not fully rational according to Muth (1961) criteria, but it generally meets the criterion of weak rationality proposed by Grant & Thomas (1999). Despite that, a paper by Hamilton (2017) entitled “Why you should never use the Hodrick-Prescott Filter” brings a series of arguments against the use of the HP filter, showing that the decomposition of a series between trend and cycle using the method can introduce spurious dynamic relations that have no basis in the data generation process. So far as we know, the use of the HP Filter in price series to generate proxies of price expectations has not been discussed since then.

The HP filter has the attractive feature of removing short-run fluctuations from the price series, but its adoption would require the reestimation of the whole series of expected prices every year, which is unfeasible for our purpose. Therefore we estimate proxies for expected output prices and salvage values of animals using ARIMA (0,1,1) models (in the first difference with a moving average component). We adopt this formulation because the series are nonstationary, and the moving average component in the first difference provides a parsimonious and smooth representation of price expectations, as shown in Figure 4, Figure *5*, and Figure *6*.

In a given year t, the expected prices for the next periods of service are assumed to be the ARIMA(0,1,1) prediction for t. ARIMA (0,1,1) prediction is used, therefore, because we assume that agents are myopic in the sense that they prospect future prices as being equal to the current price, but they can filter the observed prices from short-run fluctuations. This strategy is convenient because it requires the estimation of ARIMA predictions only one step ahead (61 predictions). The assumption of rational expectations represented by ARIMA, on the other side, would require predictions up to 7 years ahead for every year of our series, which would imply the need of estimating 427 ARIMA predictions.

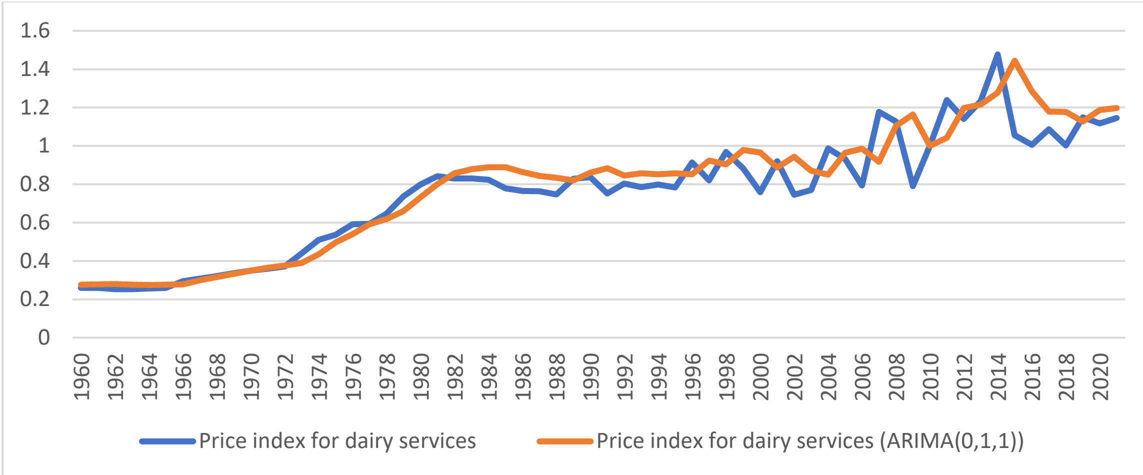


Figure 4. Observed and expected (estimated) price (index, base 2010) for dairy products in the U.S.

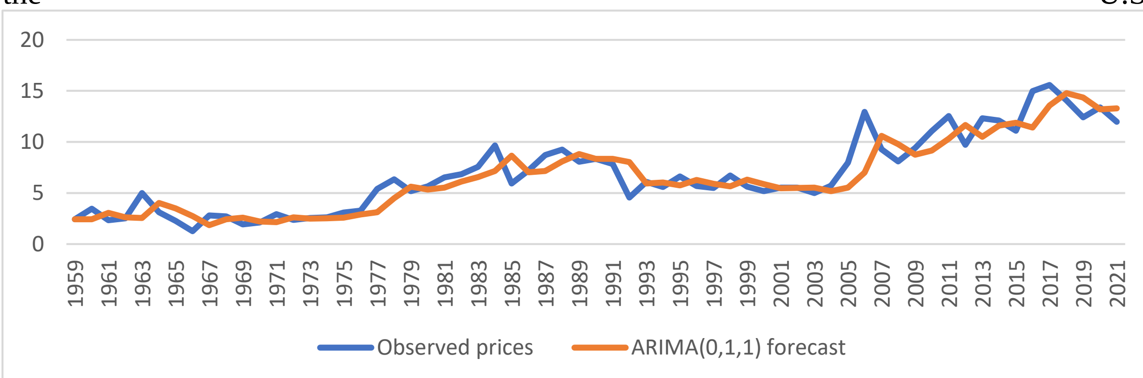


Figure 5. Observed and expected (estimated) orange prices in Florida.

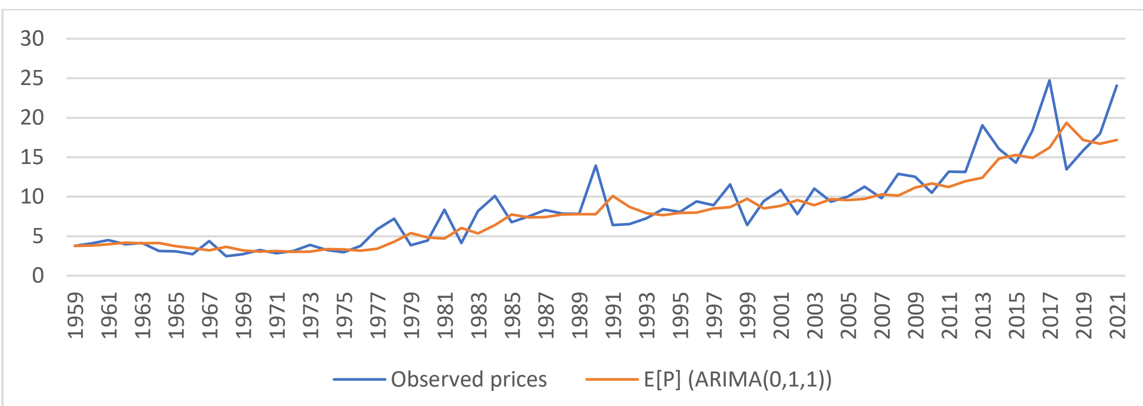


Figure 6. Observed and expected (estimated) orange prices in California.

3. Results

*3.1.*Estimates for dairy cows (U.S.)

The estimate of wealth capital stock, a measure of the market value of the dairy cow herd, we obtain by multiplying the vintage counting matrix of dairy cows by the matrix of age-price profiles. The capital services, which in our case is exactly equal to our estimate of the current value of rents from milk and slaughter of the dairy cow herd, are obtained by multiplying the elements of the vintage counting matrix of dairy cows by the corresponding elements of the matrix of age-rent profiles and adding revenues from slaughtered animals. The resulting estimate of wealth capital stock is presented in Figure 7, and the capital services are presented in Figure 8.

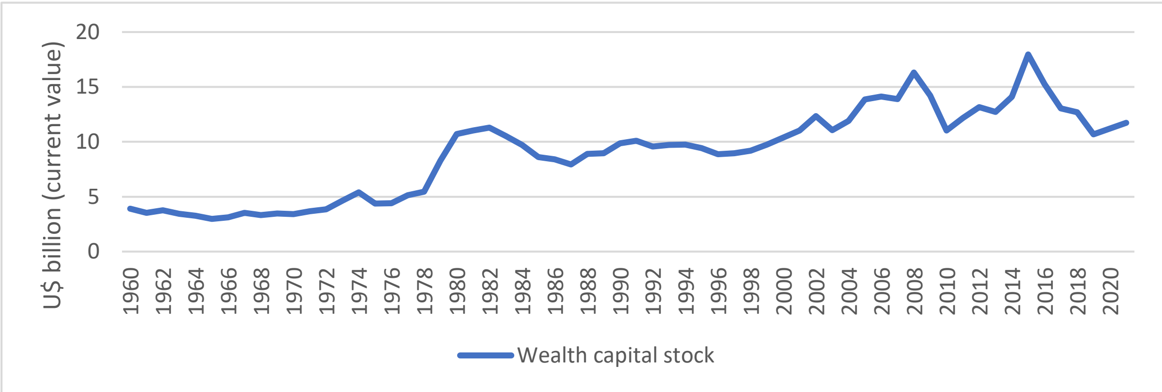


Figure 7. Wealth capital stock of dairy cows in the US (current billion U$).

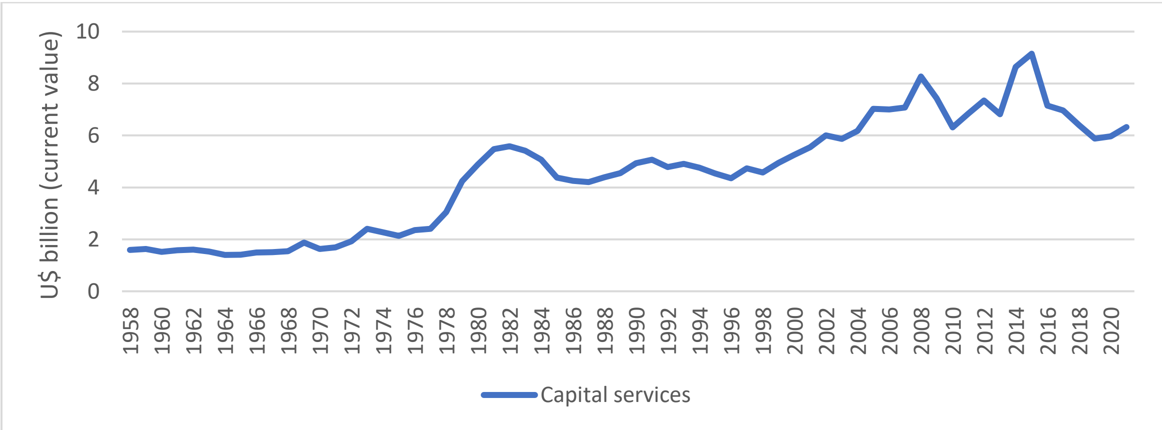


Figure 8. The capital services (value of current service flow) of dairy cows in the US (current billion $).

We estimate capital services for dairy cows in the U.S. as U$6.33 billion in current values in 2021, and a wealth capital stock of U$11.73. Our estimated stock of dairy cows is very close to the estimates of Ball et al. (2015) (Figure 9).

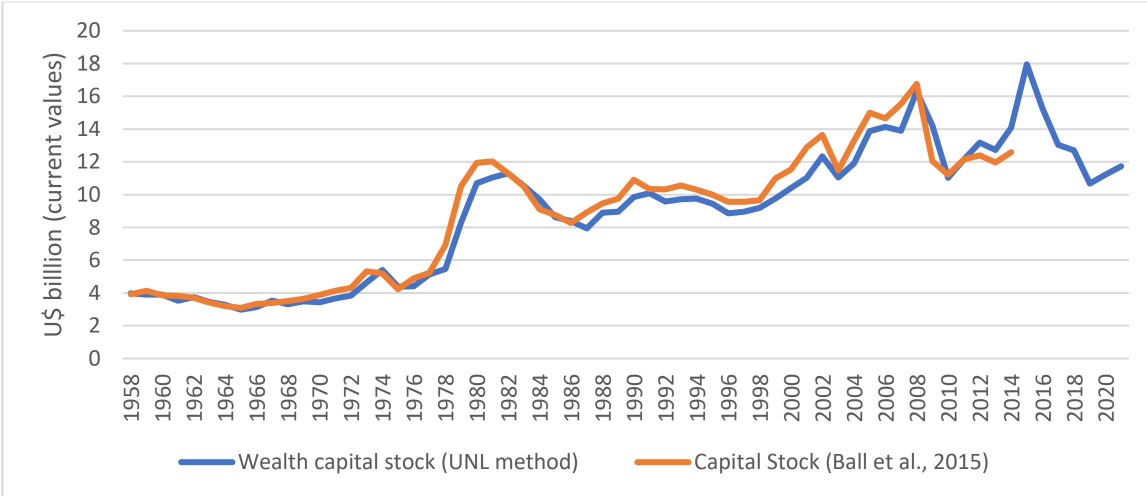


Figure 9. Comparison between our estimates (UNL method) and the method of Ball et al. (2015).

In the figure below we compare the services from the dairy cows with land services, and services from capital (excluding land) published by the USDA for the period between 1960 and 2004. In USDA estimates, capital input includes autos, farm tractors, buildings, inventories, and other machinery; and land is estimated as a constant-quality stock of land(USDA-ERS, 2023).

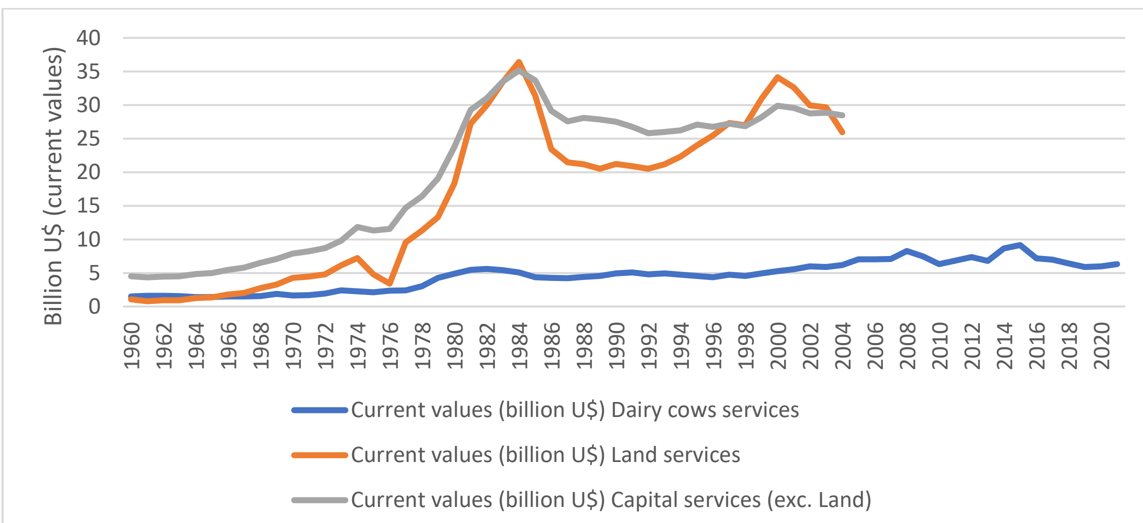


Figure 10. Services from categories of capital estimated in this study (animal categories) and other categories as estimated by USDA.

Figure 10 shows that services from dairy cows are not irrelevant. Before 1966, services from dairy cows were on occasion even greater than land services. Their relevance has decreased over time, but between 1960 and 2004 services from dairy cows were equivalent, on average, to 13.3% of the services provided by land and other forms of capital together.

3.2. Estimates for orange orchards (Florida and California)

The total bearing acreage of orange orchards and the estimated change in bearing acreage (change in the total bearing area plus mortality) are presented in Figure *11*. The bearing acreage in California has been consistently stable over the last 90 years. In Florida, the bearing acres of orange trees have increased considerably since 1930, but big decreases are observed in two moments: between 1983 and 1986, cold damaged 90% of orange trees due to the 1983 freeze and the 1985 two days of record-breaking cold (Nordheimer, 1985); after 2005, as described above, citrus greening infested Floridan orchards causing loss of trees and decrease in productivity, and winter freezes happened in 2010 (Griffin & Zierden, 2013) and 2012 (NOAA, 2010).

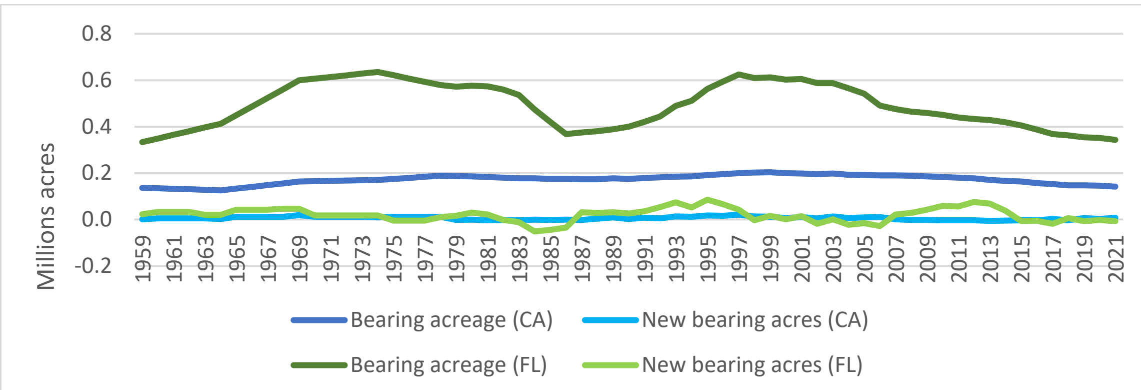


Figure 11. Bearing acreage and new bearing acres for orange orchards in Florida.

Source: own elaboration using data from NASS (2023).

Note: negative values for new bearing acres are observed when exogenous shocks caused unexpected mortality of trees.

The resulting estimate of wealth capital stocks and capital services for Florida and California are presented in Figure *12* and Figure *13*. A relevant trend observed in these estimates is the consistent increase in the participation of California, especially after the infestation of Florida orchards by citrus greening that started in 2005.

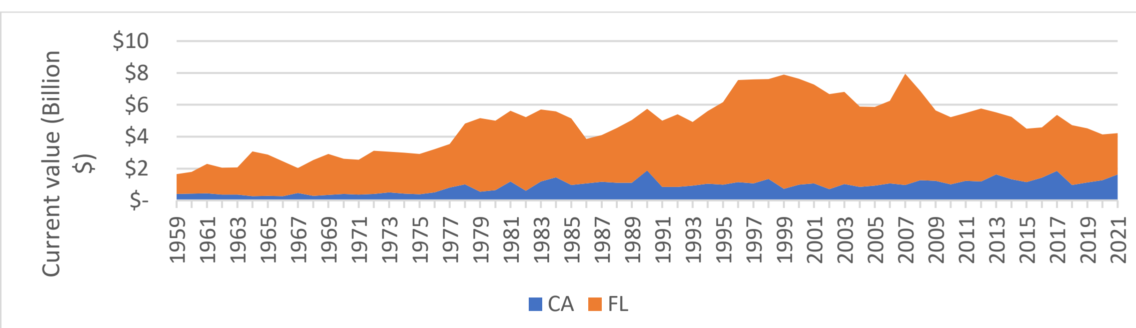


Figure 12. Wealth capital stock of orange orchards in California and Florida (current billion $).

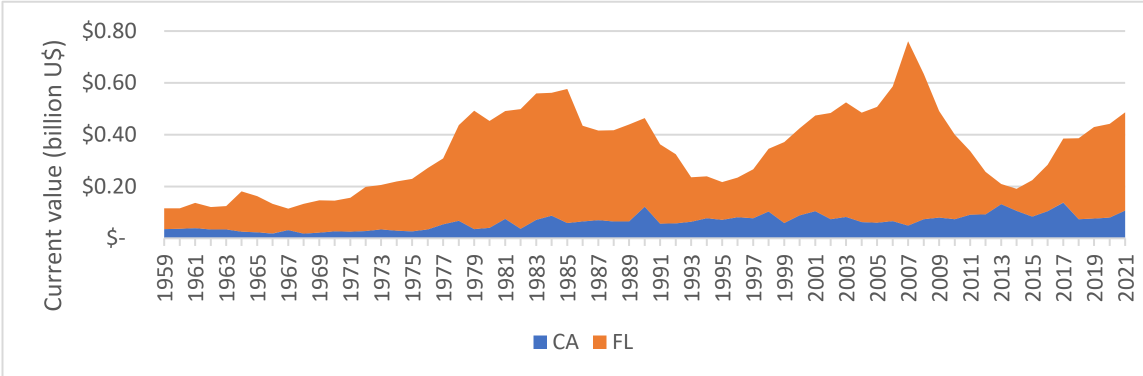
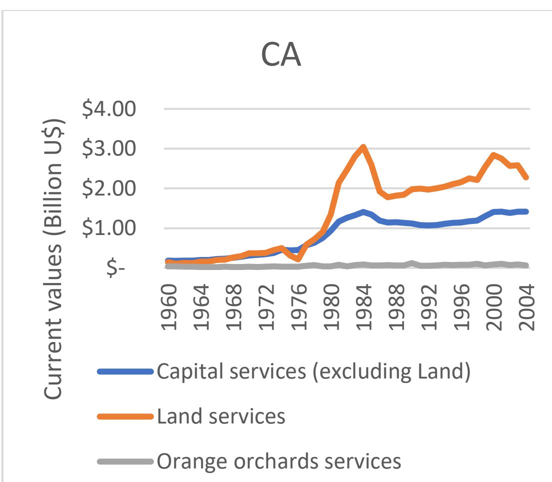


Figure 13. The capital services of orange orchards in Florida (current billion $).

According to NASS (2023), the total value of oranges production in the U.S. for the season 2019-2020 was U$ 0.87 billion. The estimated capital services for this crop in 2019 are equivalent to 40.6% of the production value, and the wealth capital stock is equivalent to 8 times that.

On average, capital services from orange orchards in California and Florida during the whole period of analysis are equivalent to 7.07% and 7.19% of their wealth stocks, respectively. However, between 2015 and 2021 capital services in Florida are equivalent on average to 8.72% of the value of the capital stock, while in California it is 7.03%. It shows that the incidence of citrus greening in Florida, by decreasing the expected lifespan of Floridan orchards, increased the relative size of the stream of services.

When compared to the estimates of capital and land services for the period 1960-2004 published by the USDA-ERS (2023), the numbers of the present study highlight the relevance of orange orchards in capital measures (Figure *14*). Capital input estimated by the USDA includes durable equipment, service buildings, and inventories (USDA-ERS, 2023).



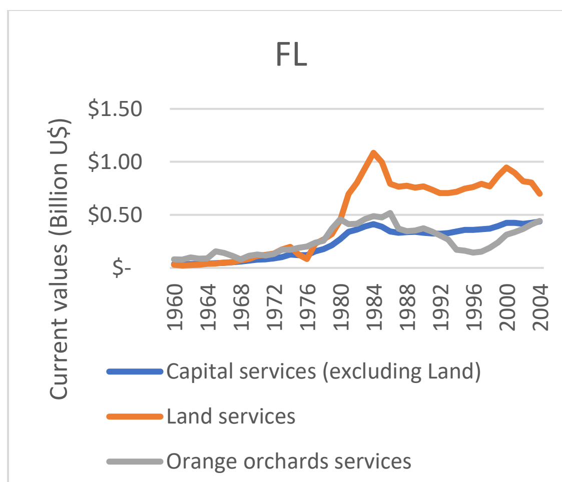


Figure 14. Capital services from orange orchards, land, and other forms of capital.

Source: own elaboration based on data from NASS (2023).

The estimated value of services from orange orchards is not large when compared to the services from land and other capital in California. For the period 1960-2004, it was equivalent, on average, to 3.8% of the estimated services from land and other forms of capital. For Florida, however, orange orchards provide services that are, on average, equivalent to 62% of what is provided by the other forms of capital measured by the USDA.

The USDA's estimates of capital and land services are estimated as the product between the real capital stock and its user costs or rental prices, and the only difference between them is that land is assumed to be the residual claimant with no depreciation (Shumway et al., 2014). In the current USDA estimates, fruit trees are included in inventories and aggregated into the Capital index (Shumway et al., 2014). However, our plots in Figure *14* show that services from orange orchards are higher than capital services (excluding land) in the whole period between 1960-2004, which is evidence that USDA is currently underestimating the user costs of inventories, or that our orchards services are being overestimated.

1.6. Conclusions

This paper contributes to the literature by describing a strategy with the proper theoretical foundations to estimate rents and prices of animals over their lifespan based on data on the price of new animals and life-cycle parameters that can be found in the literature. We use the estimated age-rents and age-prices profiles to estimate biological capital stocks and services of dairy cows for the U.S. We also proposed a method to estimate biological capital stocks and services for Florida and California orange orchards using information from university budget analyses and data on bearing acreage and output prices. Our estimates reflect well the shocks of weather and diseases in Florida orchards and show a concerning contrast between the services we calculated and the capital services estimated by the USDA.

Our results suggest the relevance of incorporating biological capital into the national accounts. In the U.S., the average services from dairy cows have been equivalent to 1.82% of total farm sales. In Florida, the average services from orange orchards were equivalent to 5.29% of the total farm sales. The results from this paper contribute to the literature by proposing theoretically sound and feasible methods for U.S. biological capital estimation to be incorporated in national accounts as well as in productivity measurement of the sector.

The methods adopted by the USDA to estimate capital stocks and services are not completely described in any publication, which makes it harder for us to work on a deep analysis to understand how the present estimates can be improved and how their inclusion in USDA's accounts and productivity analysis would impact the current numbers published by ERS.

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APPENDIX

We are seeking a simple index that we might use to adjust rents for changes in "service" prices, by which we mean the prices of outputs produced by the assets and prices of other inputs.

First, we consider appropriate service price adjustments under the assumption of a Cobb-Douglas production function with a biological asset, and solve for the dual profit function to show that the rental rate for the asset is homogeneous of degree one. This indicates that we could not use a ratio of output to variable input prices (this is homogenous of degree 0 in prices) to account in (18) for changes in market conditions.

The second example uses a dual profit function to represent a cow (the asset) that produces milk and uses variable inputs to show that the rental rate is homogeneous of degree one in prices. Again this indicates that we could not just simply use a ratio of output to input prices in (18) to adjust for changes in market conditions.

This issue is still unresolved, but we use product price indexes to reflect changes in rente caused by changes in the prices of output and other inputs related to the flow of asset services.

(a) Derivation of the rental rate of a capital asset for a Cobb Douglas production function.
For illustration purposes, let us assume a hypothetical Cobb Douglas production function with a uniform biological asset H

$$Y_t = AH_t^{\propto_H} L_t^{\propto_L} I_t^{\propto_I}$$

Where for time t, Y_t is the output; H_t is the biological capital; L_t is labor; I_t other variable inputs; and $A, \propto_H, \propto_L, \propto_I$ are parameters. Under short-run profit maximization, the producer solves

$$Max_{L_t,I_t}\, P_{Y,t} AH_t^{\propto_H} L_t^{\propto_L} I_t^{\propto_I} - P_{L,t} L_t - P_{I,t} I_t$$

The first-order conditions give

$$\propto_L\, P_{Y,t} AH_t^{\propto_H} L_t^{\propto_L - 1} I_t^{\propto_I} = P_{L,t} \rightarrow L_t = \left(\frac{\propto_L P_{Y,t} AH_t^{\propto_H} I_t^{\propto_I}}{P_{L,t}}\right)^{\frac{1}{1-\propto_L}}$$

$$\propto_I\, P_{Y,t} AH_t^{\propto_H} L_t^{\propto_L} I_t^{\propto_I - 1} = P_{I,t} \rightarrow I_t = \left(\frac{\propto_I P_{Y,t} AH_t^{\propto_H} L_t^{\propto_L}}{P_{I,t}}\right)^{\frac{1}{1-\propto_I}}$$

$$L_t = \left[\frac{\propto_L P_{Y,t} AH_t^{\propto_H}}{P_{L,t}} \left(\frac{\propto_I P_{Y,t} AH_t^{\propto_H} L_t^{\propto_L}}{P_{I,t}}\right)^{\frac{\propto_I}{1-\propto_I}}\right]^{\frac{1}{1-\propto_L}} = \left\{\frac{\propto_L}{P_{L,t}} \left[\left(\frac{\propto_I}{P_{I,t}}\right)^{\propto_I} P_{Y,t} AH_t^{\propto_H}\right]^{\frac{1}{1-\propto_I}} \left(L_t^{\propto_L}\right)^{\frac{\propto_I}{1-\propto_I}}\right\}^{\frac{1}{1-\propto_L}} =$$

$$\left\{\frac{\propto_L}{P_{L,t}} \left[\left(\frac{\propto_I}{P_{I,t}}\right)^{\propto_I} P_{Y,t} AH_t^{\propto_H}\right]^{\frac{1}{1-\propto_I}}\right\}^{\frac{1}{1-\propto_L}} L_t^{\frac{\propto_L \propto_I}{(1-\propto_I)(1-\propto_L)}}$$

$$\rightarrow L_t^{\frac{1-\propto_L-\propto_I}{(1-\propto_I)(1-\propto_L)}} = \left\{\frac{\propto_L}{P_{L,t}} \left[\left(\frac{\propto_I}{P_{I,t}}\right)^{\propto_I} P_{Y,t} AH_t^{\propto_H}\right]^{\frac{1}{1-\propto_I}}\right\}^{\frac{1}{1-\propto_L}} \rightarrow L_t = \left\{\frac{\propto_L}{P_{L,t}} \left[\left(\frac{\propto_I}{P_{I,t}}\right)^{\propto_I} P_{Y,t} AH_t^{\propto_H}\right]^{\frac{1}{1-\propto_I}}\right\}^{\frac{1-\propto_I}{1-\propto_L-\propto_I}}$$

$$\rightarrow L_t = \left[\left(\frac{\propto_L}{P_{L,t}}\right)^{1-\propto_I}\left(\frac{\propto_I}{P_{I,t}}\right)^{\propto_I} P_{Y,t}AH_t^{\propto_H}\right]^{\frac{1}{1-\propto_L-\propto_I}}$$

$$I_t = \left[\frac{\propto_I P_{Y,t}AH_t^{\propto_H}}{P_{L,t}}\left[\left(\frac{\propto_L}{P_{L,t}}\right)^{1-\propto_I}\left(\frac{\propto_I}{P_{I,t}}\right)^{\propto_I} P_{Y,t}AH_t^{\propto_H}\right]^{\frac{\propto_L}{1-\propto_L-\propto_I}}\right]^{\frac{1}{1-\propto_I}}$$

$$\rightarrow I_t = \left[\left(\frac{\propto_I}{P_{I,t}}\right)^{1-\propto_L}\left(\frac{\propto_L}{P_{L,t}}\right)^{\propto_L} P_{Y,t}AH_t^{\propto_H}\right]^{\frac{1}{1-\propto_L-\propto_I}}$$

Replacing the Marshallian demands for I_t and L_t in the production function, it is obtained the short-run profit-maximizing supply is given by

$$Y_t = AH_t^{\propto_H}\left[\left(\frac{\propto_L}{P_{L,t}}\right)^{1-\propto_I}\left(\frac{\propto_I}{P_{I,t}}\right)^{\propto_I} P_{Y,t}AH_t^{\propto_H}\right]^{\frac{\propto_L}{1-\propto_L-\propto_I}}\left[\left(\frac{\propto_I}{P_{I,t}}\right)^{1-\propto_L}\left(\frac{\propto_L}{P_{L,t}}\right)^{\propto_L} P_{Y,t}AH_t^{\propto_H}\right]^{\frac{\propto_I}{1-\propto_L-\propto_I}} =$$

$$Y_t = \left(AH_t^{\propto_H}\ \propto_L^{\propto_L}\propto_I^{\propto_I}\ \frac{1}{P_{L,t}^{\propto_L}P_{I,t}^{\propto_I}}\ P_{Y,t}^{\propto_L+\propto_I}\right)^{\frac{1}{1-\propto_L-\propto_I}}$$

Replacing the output supply and the Marshallian demands on the expression for profit

$$\pi = P_{Y,t}A\left(AH_t^{\propto_H}\ \propto_L^{\propto_L}\propto_I^{\propto_I}\ \frac{1}{P_{L,t}^{\propto_L}P_{I,t}^{\propto_I}}\ P_{Y,t}^{\propto_L+\propto_I}\right)^{\frac{1}{1-\propto_L-\propto_I}} -$$

$$P_{L,t}\left[\left(\frac{\propto_L}{P_{L,t}}\right)^{1-\propto_I}\left(\frac{\propto_I}{P_{I,t}}\right)^{\propto_I} P_{Y,t}AH_t^{\propto_H}\right]^{\frac{1}{1-\propto_L-\propto_I}} - P_{I,t}\left[\left(\frac{\propto_I}{P_{I,t}}\right)^{1-\propto_L}\left(\frac{\propto_L}{P_{L,t}}\right)^{\propto_L} P_{Y,t}AH_t^{\propto_H}\right]^{\frac{1}{1-\propto_L-\propto_I}}$$

$$= A\left(AH_t^{\propto_H}\ \propto_L^{\propto_L}\propto_I^{\propto_I}\ \frac{1}{P_{L,t}^{\propto_L}P_{I,t}^{\propto_I}}\ P_{Y,t}\right)^{\frac{1}{1-\propto_L-\propto_I}} - P_{L,t}\left[\left(\frac{\propto_L}{P_{L,t}}\right)^{1-\propto_I}\left(\frac{\propto_I}{P_{I,t}}\right)^{\propto_I} P_{Y,t}AH_t^{\propto_H}\right]^{\frac{1}{1-\propto_L-\propto_I}} -$$

$$P_{I,t}\left[\left(\frac{\propto_I}{P_{I,t}}\right)^{1-\propto_L}\left(\frac{\propto_L}{P_{L,t}}\right)^{\propto_L} P_{Y,t}AH_t^{\propto_H}\right]^{\frac{1}{1-\propto_L-\propto_I}}$$

$$\pi = \left(\frac{AH_t^{\propto_H}P_{Y,t}}{P_{L,t}^{\propto_L}P_{I,t}^{\propto_I}}\right)^{\frac{1}{1-\propto_L-\propto_I}}\left\{A\left(\propto_L^{\propto_L}\propto_I^{\propto_I}\right)^{\frac{1}{1-\propto_L-\propto_I}} - \left[\propto_L{}^{1-\propto_I}\propto_I{}^{\propto_I}\right]^{\frac{1}{1-\propto_L-\propto_I}} - \left[\propto_I{}^{1-\propto_L}\propto_L{}^{\propto_L}\right]^{\frac{1}{1-\propto_L-\propto_I}}\right\}$$

Thus, the rental rate of H is given by the equilibrating remuneration of biological capital. Under perfect competition, it is the marginal profit of a unit of capital

$$\frac{d\pi}{dH_t} = c(H,t) = \frac{\propto_H}{1-\propto_L-\propto_I}\left(\frac{AH_t^{\propto_H+\propto_L+\propto_I-1}P_{Y,t}}{P_{L,t}^{\propto_L}P_{I,t}^{\propto_I}}\right)^{\frac{1}{1-\propto_L-\propto_I}}\left\{A\left(\propto_L^{\propto_L}\propto_I^{\propto_I}\right)^{\frac{1}{1-\propto_L-\propto_I}} - \left[\propto_L{}^{1-\propto_I}\propto_I{}^{\propto_I}\right]^{\frac{1}{1-\propto_L-\propto_I}} - \left[\propto_I{}^{1-\propto_L}\propto_L{}^{\propto_L}\right]^{\frac{1}{1-\propto_L-\propto_I}}\right\}$$

$$\rightarrow c(H,t) = \frac{\propto_H}{1-\propto_L-\propto_I}\left(\frac{AH_t^{\propto_H+\propto_L+\propto_I-1}P_{Y,t}}{P_{L,t}^{\propto_L}P_{I,t}^{\propto_I}}\right)^{\frac{1}{1-\propto_L-\propto_I}}\rho\ \text{, b}$$

$$where\ \rho = A(\propto_L^{\propto_L}\propto_I^{\propto_I})^{\frac{1}{1-\propto_L-\propto_I}} - [\propto_L{}^{1-\propto_I}\propto_I{}^{\propto_I}]^{\frac{1}{1-\propto_L-\propto_I}} - [\propto_I{}^{1-\propto_L}\propto_L{}^{\propto_L}]^{\frac{1}{1-\propto_L-\propto_I}}$$

If from $t = 1$ to $t = 2$ inputs prices increase in the same proportion k_1, and output prices increase in the proportion $k_y = k_2k_1$, ceteris paribus,

$$c(H,1) = \frac{\propto_H}{1-\propto_L-\propto_I}\left(\frac{AH_t^{\propto_H+\propto_L+\propto_I-1}P_{Y,t}}{P_{L,t}^{\propto_L}P_{I,t}^{\propto_I}}\right)^{\frac{1}{1-\propto_L-\propto_I}}\rho$$

$$c(H,2) = \frac{\propto_H}{1-\propto_L-\propto_I}\left(\frac{AH_t^{\propto_H+\propto_L+\propto_I-1}k_2k_1P_{Y,t}}{(k_1P_{L,t})^{\propto_L}(k_1P_{I,t})^{\propto_I}}\right)^{\frac{1}{1-\propto_L-\propto_I}}\rho = \frac{\propto_H}{1-\propto_L-\propto_I}\left(\frac{AH_t^{\propto_H+\propto_L+\propto_I-1}k_2k_1P_{Y,t}}{(k_1P_{L,t})^{\propto_L}(k_1P_{I,t})^{\propto_I}}\right)^{\frac{1}{1-\propto_L-\propto_I}}\rho =$$
$$k_1\left(k_2^{\frac{1}{1-\propto_L-\propto_I}}\right)\frac{\propto_H}{1-\propto_L-\propto_I}\left(\frac{AH_t^{\propto_H+\propto_L+\propto_I-1}P_{Y,t}}{P_{L,t}^{\propto_L}P_{I,t}^{\propto_I}}\right)^{\frac{1}{1-\propto_L-\propto_I}}\rho$$

Then, the ratio of rental rates gives us

$$\frac{c(H,2)}{c(H,1)} = k_1\left(k_2^{\frac{1}{1-\propto_L-\propto_I}}\right)$$

which shows that the nominal changes in prices and the production elasticities to other inputs plays role in the rental rate of biological capital. The only way by which $\frac{c(H,2)}{c(H,1)} = k_2$ is if $k_1\left(k_2^{\frac{1}{1-\propto_L-\propto_I}}\right) = k_2$, which is equivalent to saying that the change in relative prices k_2 is equal to $\left(k_2^{\frac{\propto_L+\propto_I}{1-\propto_L-\propto_I}}\right) = k_1^{-1} \rightarrow k_2 = k_1^{\frac{1-\propto_L-\propto_I}{\propto_L+\propto_I}}$. In this case, one can conclude two relevant aspects of the relation between rental rates and changes in prices: due to the property of homogeneity of degree one for the profit function, not just changes in relative prices, but also the absolute changes in prices matter when estimating rental rates based on prices of the output and other inputs; if one is interested in obtaining the rental rate in real value, by deflating the prices (correcting for the general change k_1), there will never be a one-to-one relationship between the ratio of rental rates and the ratio of relative prices (output/input prices).

The formulation adopted for this appendix is based on a production function with just one asset, but the conclusions underlined in the paragraph above are also valid for the case when there is more than one kind of capital in the production function.

(b) Derivation of the rental rate of an asset (a cow) using a profit function.

Now, for simplification purposes, let us now assume a biological asset as a production unit, in the sense that the production of capital services takes place by the combination of inputs (for example feed, labor, and medicines for a dairy cow) through a given technology (genotype). Thus, for such an asset a profit function can be derived by presenting the well-known properties of an unrestricted profit function. From the homogeneity of degree one in prices:

$$\pi_s(kP_{Y,t}, kP_{X,t}) = k\pi_s(P_{Y,t}, P_{X,t})$$

If from $t = 1$ to $t = 2$ inputs prices increase in the same proportion $k_x = k_1$, and output prices increase in the proportion $k_y = k_2 k_1$, with k_1 and $k_2 > 1$, ceteris paribus,

$$\frac{\left(\frac{P_{Y,2}}{P_{X,2}}\right)}{\left(\frac{P_{Y,1}}{P_{X,1}}\right)} = \frac{\left(\frac{k_2 k_1 P_{Y,1}}{k_1 P_{X,1}}\right)}{\left(\frac{P_{Y,1}}{P_{X,1}}\right)} = k_2$$

$\pi_s(P_{Y,1}, P_{X,1})$ for $t = 1$

$\pi_s(k_1 P_{Y,1}, k_2 k_1 P_{X,1}) = k_1 \pi_s(k_2 P_{Y,1}, P_{X,1})$ for $t = 2$

If one assumes the rental rate of a biological capital is given by its marginal profit under perfect competition, we have that the ratio between the rental rate in period 2 $c(2)$ and the rental rate in period 1 $c(1)$ would be given by

$$\frac{c(2)}{c(1)} = \frac{k_1 \pi_s(k_2 P_{Y,1}, P_{X,1})}{\pi_s(P_{Y,1}, P_{X,1})}$$

Because the profit function is increasing in $P_{Y,1}$, it implies that the rental rate increases due to the change in prices, but the ratio between rental rates is not necessarily directly proportional to the ratio of relative prices.