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Time-dependent Lotkaian informetrics incorporating growth of sources and items

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ABSTRACT

In a previous article, static Lotkaian theory was extended by introducing a growth function for the items. In this article, a second general growth function – this time for the sources – is introduced. Hence this theory now comprises real growth situations, where items and sources grow, starting from zero, and at possibly different paces. The time-dependent size- and rank-frequency functions are determined and, based on this, we calculate the general, time-dependent, expressions for the h- and g-index. As in the previous article we can prove that both indices increase concavely with a horizontal asymptote, but the proof is more complicated: we need the result that the generalized geometric average of concavely increasing functions is concavely increasing.

1. Introduction

Let us have the size-frequency function of Lotka type

$$f(j) = \frac{C}{j^\alpha} \tag{1}$$

with $j \in [1, +\infty[$ and $\alpha > 1$. The theory could be extended to general α provided j is limited to a finite closed interval but this complication would make the arguments in this paper more cumbersome while, essentially, nothing new would be added; therefore we limit ourselves to $j \geq 1$, $\alpha > 1$. Hence, for every $j \geq 1$,

$$\int_j^\infty f(j')\,\mathrm{d}j' = r \tag{2}$$

denotes the total number of sources with item-density j or larger. Transforming (1) into a probability density φ leads to

$$\varphi(j) = \frac{\alpha - 1}{j^\alpha} \tag{3}$$

as is readily seen (since $\alpha > 1$).

In [5], we let the items grow in time t, using a general growth function $G(t)$ as follows: define the new item-densities at time t as

$$jG(t) = k. \tag{4}$$

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Based on this we could prove in [5] that the time-dependent size-frequency density, derived from φ is the function

$$\varphi(k,t) = G(t)^{\alpha-1}\varphi(k) \tag{5}$$

for $k \geq G(t)$. Here $\varphi(k)$ is considered to be $\varphi(k,\infty)$, i.e. for $t=\infty$.

The rank-frequency function γ, associated with f, is generally defined as (cf. [4])

$$r = \gamma^{-1}(j) = \int_j^\infty f(j')\,\mathrm{d}j' \tag{6}$$

(cf. (2)), where γ^{-1} denotes the inverse of the function γ (note that γ^{-1} strictly decreases so that $\gamma = \left(\gamma^{-1}\right)^{-1}$ is defined). Note also that $r \geq 0$.

The time-dependent rank-frequency function was proved in [5] to be

$$\gamma(r,t) = G(t)\,\gamma(r)\,. \tag{7}$$

The Hirsch-index (or h-index, shortly) is defined on a ranked list of sources (ranked in decreasing order of the number of items they produce or have), cf. [1–3,6–14]. It is the highest rank h such that all sources on rank $1,\ldots,h$ have h or more items. In the above time dependent framework it was proved that (see [5]— see also [8]) the time-dependent h-index is

$$h(t) = G(t)^{\frac{\alpha-1}{\alpha}}\,h, \tag{8}$$

where h is the h-index for $t=\infty$.

The g-index (introduced in [6,7,9]) is a solution for the drawback of the h-index that it does not increase even when the sources with the most items increase their number of items. We define the g-index to be the highest rank g such that the sources on rank $1,\ldots,g$, together, have g^2 or more items (note that h satisfies this, by definition, hence $g \geq h$). In the above framework, in [5], we proved that the time-dependent g-index is

$$g(t) = G(t)^{\frac{\alpha-1}{\alpha}}\,g, \tag{9}$$

where g is the g-index for $t=\infty$.

In the next section we will extend this theory by allowing for two general growth functions: one is the function G as in (4) (from now on called G_1) and another function G_2 acting on source ranks. We then determine the general time-dependent Lotkaian theory by proving formulae for the time-dependent size- and rank-frequency functions (using both growth functions G_1 and G_2).

Formula (5) is extended to

$$\varphi(k,t) = G_2(t)\,G_1(t)^{\alpha-1}\varphi(k) \tag{10}$$

and formula (7) is extended to

$$\gamma(s,t) = G_1(t)\,\gamma(r) \tag{11}$$

with

$$rG_2(t) = s \tag{12}$$

(the defining relation for G_2).

In the third section we show that the general time-dependent formulae for the h-index and the g-index are:

$$h(t) = G_1(t)^{1-\frac{1}{\alpha}}\,G_2(t)^{\frac{1}{\alpha}}\,h \tag{13}$$

$$g(t) = G_1(t)^{1-\frac{1}{\alpha}}\,G_2(t)^{\frac{1}{\alpha}}\,g, \tag{14}$$

where h and g are the h-index and g-index for $t=\infty$. Hence both $h(t)$ and $g(t)$ are the values at $t=\infty$, multiplied by a time factor which is a generalized geometric mean of the functions $G_1(t)$ and $G_2(t)$. We prove that such a generalized geometric mean of concavely increasing functions G_1 and G_2 is concavely increasing, hence the same is true for the functions $h(t)$ and $g(t)$, growing to their values h and g (formulae proved earlier will be repeated here) for $t=\infty$.

2. Time-dependent Lotkaian theory, incorporating general growth models for items and sources

2.1. Basic relations

Basic in this theory is the “static” law of Lotka (1), normalized so that we have a size-frequency distribution (see (3)

$$\varphi(j) = \frac{\alpha-1}{j^\alpha}, \tag{15}$$

where $j \geq 1$ and $\alpha > 1$. This distribution is considered as the "limiting" situation at time $t = \infty$, where $\varphi(j)$ denotes the density of sources with item density j (see [4]).

For the growth in time $t \geq 0$ we assume the following simple relations:

(i) Item growth: Let $G_1(t)$ be the cumulative growth distribution of the item densities expressed by (cf. (4) with $G = G_1$)

$$jG_1(t) = k. \tag{16}$$

Hence, since $j \geq 1$, we have that $k \geq G_1(t)$.

(ii) Source growth: Let $G_2(t)$ be the cumulative growth distribution of the rank densities (of the sources) expressed by (new equation)

$$rG_2(t) = s. \tag{17}$$

Hence $s \geq 0$ since $r \geq 0$.

We underline that G_1 and G_2 are arbitrary cumulative growth distributions and, of course G_1 and G_2 can be different. As cumulative growth distributions we can (and will) suppose that G_1 and G_2 are strictly increasing concave functions such that $G_1(0) = 0$, $G_2(0) = 0$, $\lim_{t\to\infty} G_1(t) = 1$, $\lim_{t\to\infty} G_2(t) = 1$. A classical example of such a function is

$$G_i(t) = 1 - a_i^t, \tag{18}$$

where $0 < a_i < 1$, $t \geq 0$, but this is only an example (we do not need (18) for our model further on).

2.2. Size-frequency functions, in function of time t

Let T denote the total number of sources at $t = \infty$. Since (17) implies

$$\frac{r}{T} G_2(t) = \frac{s}{T} \tag{19}$$

and since

$$\frac{r}{T} = \int_j^\infty \varphi(j')\,\mathrm{d}j' \tag{20}$$

denotes the fraction of sources (at $t = \infty$) with item-density j or more (cf. (2) divided by T, hence using (3)), we have, by (19) and (20) that

$$G_2(t) \int_j^\infty \varphi(j')\,\mathrm{d}j' \tag{21}$$

denotes the fraction of sources (with respect to $t = \infty$) with k or more as item-density, where

$$jG_1(t) = k \tag{22}$$

by (16). Let $\Phi(k, t)$ denote this fraction of sources. Hence

$$\Phi(k, t) = G_2(t) \int_{\frac{k}{G_1(t)}}^\infty \varphi(j')\,\mathrm{d}j'$$

$$\Phi(k, t) = G_2(t) \int_{\frac{k}{G_1(t)}}^\infty \frac{\alpha - 1}{j'^\alpha}\mathrm{d}j'$$

$$\Phi(k, t) = G_2(t) \left(\frac{G_1(t)}{k}\right)^{\alpha-1} \tag{23}$$

since $\alpha > 1$. Since

$$\Phi(k, t) = \int_k^\infty \varphi(k', t)\,\mathrm{d}k' \tag{24}$$

by definition of the time-dependent Lotka function $\varphi(k, t)$, we clearly have

$$\varphi(k, t) = -\Phi'(k, t), \tag{25}$$

where $\Phi'(k, t)$ denotes $\frac{\partial \Phi(k,t)}{\partial k}$

Consequently, by (23)

$$\varphi(k, t) = G_2(t)(\alpha - 1) \frac{G_1(t)^{\alpha-1}}{k^\alpha} \tag{26}$$

$$\varphi(k, t) = G_2(t) G_1(t)^{\alpha-1} \varphi(k), \tag{27}$$

where $k \geq G_1(t)$ and by (15). Note that, here, we extend (15) to $k \geq G_1(t)$ (by (26)).

Note that $\varphi(k,t)$ is the density of source fractions (with respect to $t=\infty$) (cf. (20) and (21)) with item-density k. Hence, denoting by T the total number of sources at $t=\infty$,

$$f(k,t) =: T\varphi(k,t) \tag{28}$$

$$f(k,t) = G_2(t)\,G_1(t)^{\alpha-1}\,T\varphi(k) \tag{29}$$

$$f(k,t) = G_2(t)\,G_1(t)^{\alpha-1}\,f(k) \tag{30}$$

denotes the actual density of sources (with respect to $t=\infty$) with item density k at time t and where $f(k)=T\varphi(k)$ denotes the same at $t=\infty$. Note that also here (15) is extended to $k \geq G_1(t)$.

2.3. Total number of sources and items at time t

The above function $f(k,t)$ already allows one us calculate
$T(t)$ = the total number of sources at time t
$A(t)$ = the total number of items at time t.
We have, by the definition of $f(k,t)$ (cf. (29)) and since $k \geq G_1(t)$:

$$\begin{aligned} T(t) &= \int_{G_1(t)}^{\infty} f(k,t)\,\mathrm{d}k \\ T(t) &= G_2(t)\,G_1(t)^{\alpha-1}\,T\int_{G_1(t)}^{\infty}\varphi(k)\,\mathrm{d}k \\ T(t) &= G_2(t)\,G_1(t)^{\alpha-1}\,TG_1(t)^{1-\alpha} \\ T(t) &= G_2(t)\,T \end{aligned} \tag{31}$$

a logical result. In the same way, for $\alpha > 2$, we have (cf. (29))

$$\begin{aligned} A(t) &= \int_{G_1(t)}^{\infty} kf(k,t)\,\mathrm{d}k \\ &= TG_2(t)\,G_1(t)^{\alpha-1}\int_{G_1(t)}^{\infty} k\varphi(k)\,\mathrm{d}k \\ &= TG_2(t)\,G_1(t)^{\alpha-1}\,\frac{\alpha-1}{\alpha-2}G_1(t)^{2-\alpha}. \end{aligned} \tag{32}$$

But, as is readily seen, on $t=\infty$ (cf. [4, Chapter 2]), since $\alpha > 2$

$$\begin{aligned} \mu = \frac{A}{T} &= \frac{\int_1^{\infty} k\varphi(k)\,\mathrm{d}k}{\int_1^{\infty}\varphi(k)\,\mathrm{d}k} \\ &= \frac{\alpha-1}{\alpha-2}. \end{aligned} \tag{33}$$

(T = the total number of sources at $t=\infty$, A = the total number of items at $t=\infty$).
Hence, (33) in (32) yields

$$A(t) = AG_1(t)\,G_2(t),$$

also a logical result since items at t are determined by the items in the already existing sources; the former one is determined by G_1 and the latter one by G_2.

Since rank-frequency functions are equivalent with size-frequency functions (by the general relation (6), but now t-dependent) we are now in a position to calculate the time-dependent rank-frequency function $\gamma(s,t)$.

2.4. The rank-frequency function, in function of time t

Since, at t, the rank-densities are denoted by s via (17) and by (6), interpreted at time t, we have (the inverse refers to the variable k)

$$\begin{aligned} s = s(t) = \gamma^{-1}(k,t) &= \int_k^{\infty} f(k',t)\,\mathrm{d}k' \\ &= TG_2(t)\,G_1(t)^{\alpha-1}\int_k^{\infty}\varphi(k')\,\mathrm{d}k', \end{aligned} \tag{34}$$

by (29). Hence, using (15)

$$s = s(t) = \frac{C}{\alpha-1}\,\frac{G_2(t)\,G_1(t)^{\alpha-1}}{k^{\alpha-1}}$$

denoting $T(\alpha-1)=C$ (hence $f(k)=\frac{C}{k^{\alpha}}$). This yields

$$k=\gamma(s,t)=\frac{C^{\frac{1}{\alpha-1}}}{((\alpha-1)s)^{\frac{1}{\alpha-1}}}G_2(t)^{\frac{1}{\alpha-1}}G_1(t).$$

Invoking (17) yields

$$k=\gamma(s,t)=\frac{C^{\frac{1}{\alpha-1}}}{((\alpha-1)r)^{\frac{1}{\alpha-1}}}G_1(t)$$

$$\gamma(s,t)=\gamma(r)G_1(t) \tag{35}$$

with r and s related as in (17). Note that (35) follows from the fact that $f(k)=\frac{C}{k^{\alpha}}$ and by applying the same calculation as performed here (but for $t=\infty$, hence $G_1(\infty)=G_2(\infty)=1$). In fact the result can also be found in [4, Exercise II.2.2.6 (p. 134)] and its proof is also given in [10, Appendix].

In the next section, we will apply these results in the calculation of the general forms of the time-dependent h- and g-indices.

3. Formulae for the time-dependent h- and g-indices and properties of these functions of time

3.1. The time-dependent h-index

The h-index in this model is defined to be $h(t)$ such that

$$\int_{h(t)}^{\infty}f(k,t)\,\mathrm{d}k=h(t). \tag{36}$$

Hence by (29) and (15) we have

$$TG_2(t)G_1(t)^{\alpha-1}\int_{h(t)}^{\infty}\frac{\alpha-1}{k^{\alpha}}\mathrm{d}k=h(t).$$

So

$$h=h(t)=(TG_2(t))^{\frac{1}{\alpha}}G_1(t)^{\frac{\alpha-1}{\alpha}}. \tag{37}$$

Invoking that, for $t=\infty$

$$h=h(\infty)=T^{\frac{1}{\alpha}} \tag{38}$$

(see [12,10]). So (37) and (38) yield

$$h(t)=G_1(t)^{1-\frac{1}{\alpha}}G_2(t)^{\frac{1}{\alpha}}h. \tag{39}$$

Note that the time-dependent h-index is proportional to the generalized geometric mean of the growth functions $G_1(t)$ and $G_2(t)$. In the following we will study properties of this generalized geometric mean.

3.2. The time-dependent g-index

There are two, equivalent, ways to define the g-index (at time t), denoted $g(t)$: if

$$\int_{k}^{\infty}k'f(k',t)\,\mathrm{d}k'=g(t)^2 \tag{40}$$

then

$$g(t)=\gamma^{-1}(k,t). \tag{41}$$

Equivalently, $g(t)$ is defined as

$$\int_0^{g(t)}\gamma(r,t)\,\mathrm{d}r=g(t)^2. \tag{42}$$

The latter approach has been followed in [5] (but only using the growth function G_1—there denoted G). Here we will follow the former approach. Formula (40) yields, using (15) and (19) (and the notation $C=T(\alpha-1)$, already used above):

$$G_2(t)G_1(t)^{\alpha-1}\int_k^{\infty}\frac{C}{k'^{\alpha-1}}\mathrm{d}k'=g(t)^2$$

$$G_2(t)G_1(t)^{\alpha-1}\frac{C}{\alpha-2}k^{2-\alpha}=g(t)^2, \tag{43}$$

supposing $\alpha > 2$. But (34) yields (using (15) again)

$$\gamma^{-1}(k,t) = G_2(t)\,G_1(t)^{\alpha-1}\int_k^\infty \frac{C}{k'^{\alpha}}\mathrm{d}k'$$

$$g(t) = \gamma^{-1}(k,t) = G_2(t)\,G_1(t)^{\alpha-1}\,\frac{C}{\alpha-1}k^{1-\alpha} \tag{44}$$

by (41). So, solving (44) for k, yields

$$k = \left(\frac{\alpha-1}{C}\frac{g(t)}{G_2(t)}\right)^{\frac{1}{1-\alpha}} G_1(t) \tag{45}$$

(45) in (43) yields, after some calculation and using that $T = \frac{C}{\alpha-1}$:

$$g(t) = G_1(t)^{1-\frac{1}{\alpha}}\,G_2(t)^{\frac{1}{\alpha}}\left(\frac{\alpha-1}{\alpha-2}\right)^{\frac{\alpha-1}{\alpha}} T^{\frac{1}{\alpha}}. \tag{46}$$

Invoking that, for $t=\infty$,

$$g = g(\infty) = \left(\frac{\alpha-1}{\alpha-2}\right)^{\frac{\alpha-1}{\alpha}} T^{\frac{1}{\alpha}} \tag{47}$$

(see [7]). So (47) in (46) yields

$$g(t) = G_1(t)^{1-\frac{1}{\alpha}}\,G_2(t)^{\frac{1}{\alpha}}\,g. \tag{48}$$

Hence $g(t)$ has the same proportionality factor as $h(t)$ (see (39)). We will now study this proportionality factor which determines the evolution of $h(t)$ and $g(t)$ in time.

3.3. Properties of $G_1(t)^{1-\frac{1}{\alpha}}G_2(t)^{\frac{1}{\alpha}}$

Since $G_1(t)$ and $G_2(t)$ are cumulative growth distributions we have that

$$G_1(0) = G_2(0) = 0$$
$$\lim_{t\to\infty} G_1(t) = \lim_{t\to\infty} G_2(t) = 1$$

and that G_1 and G_2 are strictly increasing in t and this increase is concave (example: (18) but we do not need this special case here).

So it is then trivial that $h(t)$ strictly increases from 0 to h (its maximal value, being $h(\infty)$) and that $g(t)$ strictly increases from 0 to $g\ (\geq h)$.

The lemma in the Appendix shows that the generalized geometric mean of strictly increasing concave functions is strictly increasing and concave so that also $h(t)$ and $g(t)$ are strictly increasing and concave. Of course, since the g-index is larger than or equal to the h-index we also have, for every t:

$$g(t) \geq h(t). \tag{49}$$

4. Conclusions and open problems

In this paper we studied the aspect of time-dependence in the evolution of a Lotkaian system. Source and item densities are growing in time using two general cumulative growth distributions. Using this general framework yields formulae for the time-dependent size- and rank-frequency functions in the function of the final situation at $t=\infty$, where we suppose we have a Lotkaian system. We show that at every time t, we have a Lotkaian system with the same Lotka exponent, but where the growth is dependent on – in addition to the two growth distributions – this Lotka exponent.

Similar results are proved for the time-dependent h- and g-indices. Here we prove that both indices are proportional to their values at $t=\infty$, and where the time-dependent proportionality factor is a generalized geometric mean of the two growth distributions. Also here the Lotka exponent is involved. We prove in a lemma in the Appendix that a general geometric mean of strictly increasing concave functions is strictly increasing and concave. Hence the same is true for the time-dependent h- and g-indices.

We formulate as an open problem the definition of other growth processes of sources and items, where the growth functions are acting on the source- and item-densities in a nonlinear way and the derivation from this framework of the time-dependent size- and rank-frequency functions and the time-dependent h- and g-indices.

Appendix

Let x and y be two positive real numbers. We say that z is a generalized geometric average of x and y if there exists a $\lambda \in]0, 1[$ such that

$$z = x^{\lambda} y^{1-\lambda}. \tag{A.1}$$

The classical geometric mean is given when $\lambda = \frac{1}{2}$: then $z = \sqrt{xy}$.
In Section 3 we found that

$$h(t) = G_1(t)^{1-\frac{1}{\alpha}} G_2(t)^{\frac{1}{\alpha}} h \tag{A.2}$$

$$g(t) = G_1(t)^{1-\frac{1}{\alpha}} G_2(t)^{\frac{1}{\alpha}} g \tag{A.3}$$

hence $h(t)$ and $g(t)$ are equal to their values at $t = \infty$ multiplied by a generalized geometric mean of the growth functions $G_1(t)$ and $G_2(t)$ (note, indeed, that, since $\alpha > 1$ we have that $\lambda = 1 - \frac{1}{\alpha} \in]0, 1[$).

We have the following general lemma.

Lemma. *Let G_1, G_2 be two functions of the variable t which are strictly increasing and concave. Then their generalized geometric average (for $\alpha > 1$)*

$$G(t) =: G_1(t)^{1-\frac{1}{\alpha}} G_2(t)^{\frac{1}{\alpha}} \tag{A.4}$$

is strictly increasing and concave.

Proof. That G is strictly increasing in t is trivial. For the concavity we need to calculate G''. We have

$$G'(t) = \frac{\alpha-1}{\alpha}\left(\frac{G_1(t)}{G_2(t)}\right)^{-\frac{1}{\alpha}} G_1'(t) + \frac{1}{\alpha}\left(\frac{G_1(t)}{G_2(t)}\right)^{\frac{\alpha-1}{\alpha}} G_2'(t) \tag{A.5}$$

$$\begin{aligned} G''(t) \;=\; & \frac{\alpha-1}{\alpha}\left(-\frac{1}{\alpha}\right)\left(\frac{G_1(t)}{G_2(t)}\right)^{-\frac{1}{\alpha}-1} \frac{G_2(t)G_1'(t) - G_1(t)G_2'(t)}{G_2^2(t)} .G_1'(t) + \frac{\alpha-1}{\alpha}\left(\frac{G_1(t)}{G_2(t)}\right)^{-\frac{1}{\alpha}} G_1''(t) \\ & + \frac{1}{\alpha}\frac{\alpha-1}{\alpha}\left(\frac{G_1(t)}{G_2(t)}\right)^{\frac{\alpha-1}{\alpha}-1} \frac{G_2(t)G_1'(t) - G_1(t)G_2'(t)}{G_2^2(t)} .G_2'(t) + \frac{1}{\alpha}\left(\frac{G_1(t)}{G_2(t)}\right)^{\frac{\alpha-1}{\alpha}} G_2''(t)\,. \end{aligned}$$

The second and fourth terms are clearly strictly negative since G_1 and G_2 are concave. The first and third term, together, equal

$$\begin{aligned} & \frac{\alpha-1}{\alpha^2}\left(\frac{G_1(t)}{G_2(t)}\right)^{-\frac{1}{\alpha}} \frac{G_2(t)G_1'(t) - G_1(t)G_2'(t)}{G_2^2(t)} \left[-\frac{G_2(t)}{G_1(t)}G_1'(t) + G_2'(t)\right] \\ & = \frac{\alpha-1}{\alpha^2}\left(\frac{G_1(t)}{G_2(t)}\right)^{-\frac{1}{\alpha}} \frac{1}{G_1(t)G_2^2(t)} \left[-\left(G_2(t)G_1'(t) - G_1(t)G_2'(t)\right)^2\right] \\ & < 0, \quad \text{since } \alpha > 1. \end{aligned}$$

So $G''(t) < 0$ for all t and hence $G(t)$ is concave. □

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