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The treatment of long-lived, carbon-containing products in inventories of carbon dioxide emissions to the atmosphere

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Abstract

The United Nations Framework Convention on Climate Change (UNFCCC) requires that all parties to the convention periodically report their emissions of greenhouse gases and the Intergovernmental Panel on Climate Change (IPCC) has published guidelines on how to estimate these emissions. Estimating carbon dioxide (CO₂) emissions is complicated by the fact that consumption of fossil-fuels and harvesting of forests do not necessarily mean that the contained C has been released to the atmosphere as CO₂. Some fractions of fossil-fuels and harvested wood are incorporated into products that have lifetimes ranging from months to centuries. The IPCC methodology addresses durable products by assuming that some prescribed fraction goes to permanent storage while the remainder is oxidized instantly. The question posed here is whether the annual increase in stocks of durable products, i.e. the difference between the rates of production and oxidation, can be reasonably estimated as a simple fraction of their current rate of production. Although the annual stock change can be described as a simple fraction of annual production when production is growing exponentially and oxidation is a first order decay process, a description of annual stock changes needs to consider how both production and oxidation are evolving with time, regardless of the functional forms of these changes with time.

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1. Introduction

The primary driving force for global climate change is emissions of the greenhouse gas carbon dioxide (CO₂) from combustion of fossil-fuels. Clearing of forests has been another major contributor to the increasing concentration of atmospheric CO₂, although it is currently on the order of 25% of emissions from fossil-fuels. In order to understand the historic increase of atmospheric CO₂ and the potential for additional build-up of CO₂ in the atmosphere, the rate of release of CO₂ to the atmosphere has been estimated (Marland et al., 2001; Houghton and Hackler, 2001). These estimates of CO₂ flows are based on the rate at which fossil-fuels are consumed and the rate at which land is converted from a land cover with high carbon density (e.g. forests and grasslands) to a land cover with low carbon density (e.g. croplands and urban areas).

Estimation of CO₂ emissions from fossil-fuels is complicated by the fact that fossil-fuels that are consumed are not necessarily oxidized immediately to CO₂. A significant fraction of petroleum production, for example, is used as

lubricants, plastics, asphalt, and other products that are oxidized over periods ranging from months to decades, or even longer. Some fossil-fuels find their way into products or landfills where they are not oxidized over periods of current interest for global climate change. Similarly, some fraction of the material removed from forests is not immediately oxidized with the harvesting of the forest, but rather is converted into paper, packaging, lumber, etc. and is oxidized over an extended period of time. In the US, 8% of fossil-fuel use is for non-energy purposes (US EPA, 2001), and petrochemicals account for 7% of global oil consumption (Gielen, 1997). Some 12% of fossil-fuel consumption in Western Europe is for non-energy uses, and in The Netherlands 26% of petroleum is used for synthetic organic chemicals (Gielen, 1997). The challenge is furthered for national emissions estimates in that, for example, 75% of petrochemical products produced in The Netherlands are exported and not oxidized within The Netherlands. Skog and Nicholson (1998) estimate that US wood consumption in 1992 included 147 million tonnes of carbon and that the increase in stocks of wood and paper products (in use and in landfills) contained a mass of carbon that was equivalent to 4.5% of US carbon emissions from fossil-fuel use in 1990. Buchanan and Levine (1999) have estimated that the typical,

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68 small New Zealand home, with light wood framing, contains
69 34 kg C/m^2 .

70 If we want an accurate understanding of the flows of carbon
71 in the terrestrial system, and if we want accurate estimates
72 of emissions of CO_2 to the atmosphere, we need to
73 focus on the flows of organic-derived materials with enough
74 detail to accurately reflect the time path over which they are
75 oxidized to CO_2 .

76 There is further interest in estimating greenhouse gas
77 emissions as concern rises about trying to mitigate anthropo-
78 genic changes in climate. The United Nations Framework
79 Convention on Climate Change (UNFCCC) requires that
80 countries submit a periodic inventory of their emissions of
81 greenhouse gases. The Convention has been ratified by over
82 185 countries and entered into force on March 21, 1994. The
83 requirements of the UNFCCC would be strengthened with
84 ratification of the Kyoto Protocol. The Kyoto Protocol seeks
85 to add to the UNFCCC binding, quantitative national limits
86 on the emission of greenhouse gases to the atmosphere. At
87 the time of this writing, The Kyoto Protocol has not yet been
88 ratified by enough countries to enter into force, although
89 entry into force in the near future appears likely.

90 Estimating emissions of CO_2 from non-fuel uses of
91 petroleum and wood products could be done with detailed
92 statistics on the production and fate of all organic products,
93 but the number and variety of products is very large and
94 the accounting challenge would be considerable. We search
95 for a simpler approach that will estimate the flow of CO_2
96 to the atmosphere with sufficient accuracy, but will do so
97 with methods and data that are widely accessible to ana-
98 lysts interested either in understanding the global cycling
99 of carbon or in monitoring efforts to reduce emissions to
100 the atmosphere.

101 2. Methods

102 In 1984, Marland and Rotty described an approach for
103 producing an annual inventory of CO_2 emissions to the at-
104 mosphere from consumption of fossil-fuels. This approach
105 recognized that part of the fuel is oxidized promptly during
106 combustion but that part of the flow is to fossil-fuel prod-
107 ucts of varying life expectancy. They offered a simplified
108 method for dealing with the fraction of fossil-fuel that goes
109 to non-fuel uses. The basic approach of Marland and Rotty
110 (1984) is now embodied in guidelines for national inven-
111 tories of greenhouse gas emissions published by the Inter-
112 governmental Panel on Climate Change (IPCC, 1997) and
113 it is the IPCC guidelines that are used in national reporting
114 under the UNFCCC (2000). This approach provides a fun-
115 damental simplification for dealing with durable products
116 that is useful because of its simplicity and because it relies
117 only on easily available, current year data. It can be used by
118 any country, or other entity, with basic data on the supply
119 and demand for non-fuel products. The approach is indeed
120 a simplification, however, and is strictly valid under limited

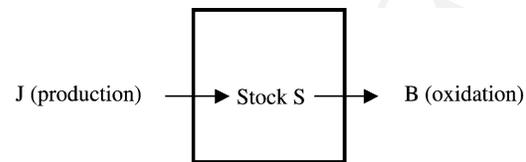


Fig. 1. The stock S of carbon in a pool of products will be increased by the rate of production, flow J , and decreased by rate of oxidation, flow B . If the rate of oxidation B is less than the rate of production J , the stock will increase. If flow B is a function of the stock, $B = f(S)$, then it may be possible to estimate the change in stock $\Delta S = J - B$ as a function of J only.

121 conditions. In this paper we explore the conditions under
122 which the Marland and Rotty/IPCC approach is appropriate
123 and illustrate what is necessary in order to generate more
124 accurate inventories of CO_2 emissions.

125 Our concern is with the extent to which the rate of oxi-
126 dation of products from fossil-fuels or forest harvest differs
127 from their rate of production, i.e. the extent to which there
128 is a net accumulation or loss of carbon in durable prod-
129 ucts. With respect to an increase in the stock of carbon in
130 long-lived petroleum products, Marland and Rotty (1984)
131 wrote, “over long time scales the amount oxidized each year
132 will equal the amount produced each year as long as the
133 amount produced each year is nearly constant. When the
134 average lifetime of the unoxidized materials is very long or
135 when the amount produced each year is growing, there is
136 a net amount that remains unoxidized.” Marland and Rotty
137 (1984) then suggested the assumption that for products with
138 increasing rates of production, the annual increase in stocks
139 (S in Fig. 1) could be approximated as a function of their rate
140 of production (J in Fig. 1). In particular, they suggested that
141 the increase in carbon stocks in products each year could be
142 represented as a simple fraction of the annual production for
143 certain categories of products, i.e. $\Delta S/J$ could be treated as a
144 constant. As an example, Marland and Rotty suggested that
145 an amount equivalent to “about 40% of the LPG and ethane
146 produced from natural gas processing plants ends up in ma-
147 terials which are not soon oxidized. (That is, for a given
148 year, oxidation of current year production plus the sum from
149 continuing oxidation of previous years’ production amounts
150 to 60% of current year production.)”

151 The IPCC methodology books (IPCC, 1997) do not quite
152 convey the same nuance that we are concerned about the
153 balance between production and destruction and, from them,
154 the change in stocks over time; but they accomplish the same
155 thing mathematically by assuming that some fraction of pro-
156 duction goes into permanent storage while the remainder is
157 oxidized in the year of production. Table 1 shows the num-
158 bers suggested by the IPCC (1997) and, more recently, by
159 the US EPA (2001) to describe the relationship between the
160 rate of current production of various products and the in-
161 crease in stocks of those products. Numbers between 0 and 1
162 suggest that carbon stocks are increasing over time as a frac-
163 tion between 0 and 100% of the current rate of production.

Table 1

Coefficients suggested by the IPCC and US EPA for estimating the annual rate at which the carbon contained in non-fuel petroleum products accumulates in the products rather than being released to the atmosphere as CO₂

Fuel product	Equivalent fraction of annual production stored in products (IPCC, 1997)	Equivalent fraction of annual production stored in products (US EPA, 2001)
Naphtha ^a	0.80	0.91
Lubricants	0.50	0.09
Bitumen	1.00	1.00
Coal oils and tars	0.75	
Natural gas ^a	0.33	
Gas/diesel oil ^a	0.50	0.50
LPG ^a	0.80	0.91
Ethane ^a	0.80	

The coefficient is multiplied by the annual production to get the increase in stocks.

^a When used as a feedstock.

164 An alternate approach to treating durable products is one
165 that has evolved from the ideas of Okken and Kram (1990)
166 (see also, for example, Gielen, 1997). This approach (ma-
167 terial flow analysis) tries to follow, statistically, the multi-
168 tude of processes and products involved in the non-fuel uses
169 of fossil-fuels and divides them into short- and long-lived
170 products. The short-lived products are assumed to oxidize
171 in the year of production and the long-lived products are as-
172 sumed to persist indefinitely. The only deviation from this
173 is that combustion of long-lived products at waste disposal
174 facilities is captured and reported as emissions from waste
175 disposal (organic materials placed in modern landfills can
176 be expected to lose very little carbon mass over century
177 time scales). In essence, this treatment assumes that there is
178 no oxidation of products in use and oxidation of long-lived
179 products is captured only if it results from waste combus-
180 tion. The US national reports to the UNFCCC (US EPA,
181 2001) follow this philosophy. The IPCC methodology also
182 supports this approach and suggests 20 years as the demar-
183 cation between short- and long-lived products. Gielen (1997),
184 in fact, suggests that only products with life times greater
185 than 20 years should be considered for correction of the as-
186 sumption that fossil-fuel products are oxidized immediately
187 at consumption.

188 One problem with the material flow analysis approach is
189 that it requires finely resolved data on many more products
190 and processes than treated in the IPCC methodology, and is
191 therefore very data intensive. Even its proponents recognize
192 that the approach will be of limited utility for many countries
193 where data are less readily available than in the US and
194 The Netherlands. Required data may often be proprietary or
195 expensive to obtain. Gielen (1997) suggests that “whether
196 the difference between the material flow method and the
197 IPCC methodology warrants the far more elaborate material
198 flow accounting calculations should be judged within the
199 UNFCCC framework.”

200 Non-fuel use of petrochemicals involves thousands of
201 products, but even a detailed material flow analysis can fo-
202 cus primarily on less than 50 chemicals that make up the
203 bulk of production (Gielen and Patel, 1999). With sufficient
204 product and sectoral break-down, products and fates can
205 be pointedly identified; but the method still assumes that
206 each product is either oxidized immediately or not at all.
207 Gielen (1997) writes, for example, “Contrary to the (IPCC)
208 guidelines, all lubricants are considered short-lived appli-
209 cations, because in the natural environment they are more
210 readily converted into CO₂ than, for example, plastics and
211 because their ultimate conversion to CO₂ cannot be traced
212 from other statistics.” Gielen and Patel (1999) suggest, on
213 the basis of material flow analysis, that carbon storage in
214 products is less than is estimated from the IPCC guidelines.
215 In fact, the agreement between the two estimates for The
216 Netherlands (IPCC method versus materials flow approach)
217 reported by Gielen (1997) seems remarkably good, within
218 25%, given that he suggests the materials flow estimate may
219 be $\pm 15\%$.

220 We continue to investigate the idea that the change in
221 stocks of non-fuel products could be simply estimated as a
222 function of their rate of production. In this paper, we explore
223 the functional forms of J and B (Fig. 1) with respect to time
224 and show how the change in stocks (ΔS) is then related to
225 the rate of production (J). Our basic question is whether it is
226 indeed reasonable to represent the annual change in stocks
227 as a simple multiple of the current rate of production (i.e.
228 $\Delta S = \text{constant} \times J$ or $\Delta S/J = \text{constant}$). When there is not
229 a simple relationship between ΔS and J , we ask what ad-
230 ditional data are required in order to approximate the rate
231 of oxidation of the carbon that is used for durable products.
232 Our intention is to capture in this representation both the
233 oxidation of products during waste processing and their ox-
234 idation during use. The latter may be particularly useful for
235 considering durable wood products.

236 For this paper, we have modeled the change in stocks of
237 petrochemical and wood products using differential equa-
238 tions to describe the rates of production and destruction.
239 Solutions to the differential equations were achieved using
240 the standard differential equations tools available on Maple
241 software produced by Waterloo Maple Inc. The solutions of
242 the equations are exact analytical solutions, not approxima-
243 tions, that were then plotted in the desired formats.

244 3. Estimating stock change as a function of 245 production rate

246 3.1. A simple illustration

247 Consider a specific (new) product, derived from petroleum
248 or wood. We assume that the product is produced at a con-
249 stant rate and oxidizes during use with a half-life of 1 year.
250 Oxidation is described here as a first order decay where the
251 rate of decay is proportional to the amount of stock present

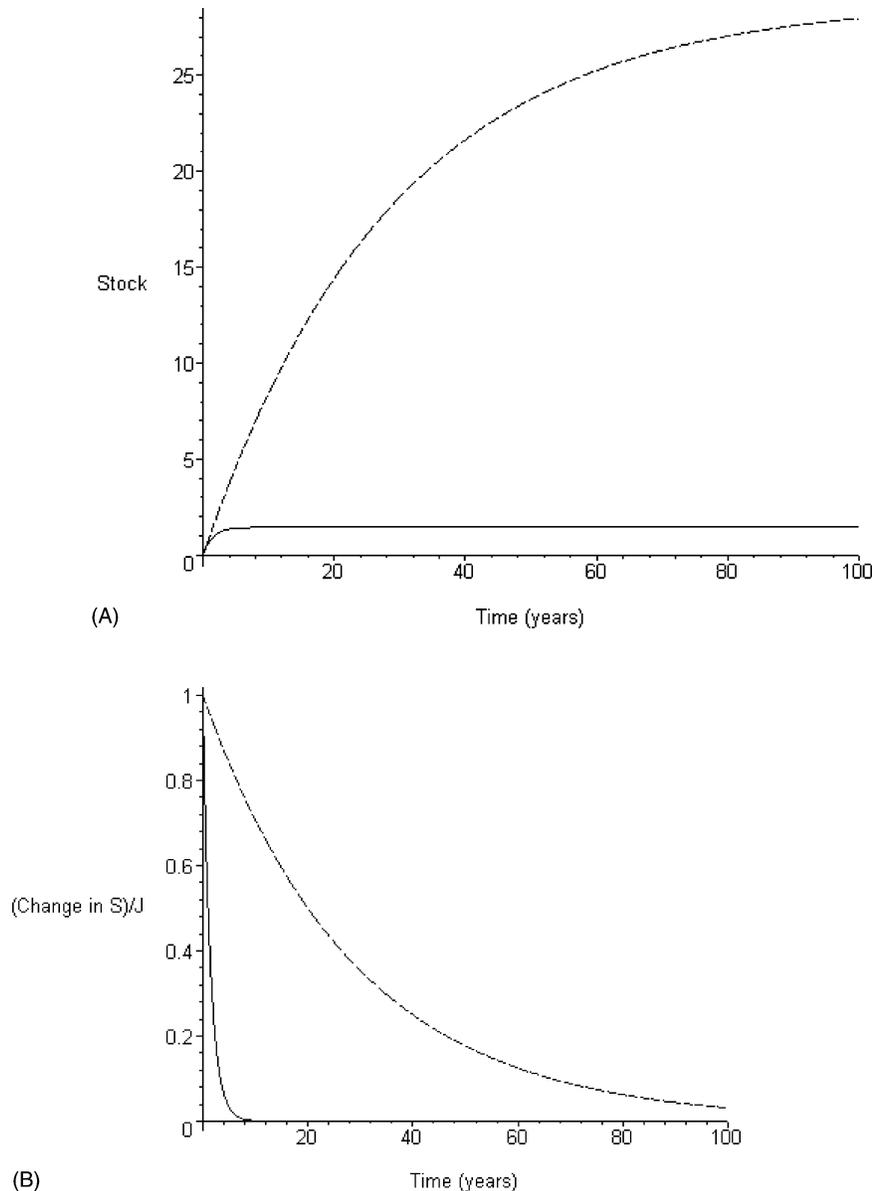


Fig. 2. When the rate of production of a product is constant at $J = 1$ unit per year and decay is first order with a half-life of 1 year, the stock will increase for about 6 years (six half-lives) before reaching a steady state near 1.4 times the annual rate of production ((A) solid line). Simultaneously, the ratio between the change in stocks and the rate of production ($\Delta S/J$) will decline rapidly for about 6 years before approaching an asymptote at 0, when the rate of production is exactly balanced by the rate of oxidation ((B) solid line). When the rate of production of a product is constant at $J = 1$ unit per year and decay is first order with a half-life of 20 years, the stock will increase for about 120 years (six half-lives) before reaching a steady state near 29 times the annual rate of production ((A) dashed line). Simultaneously, the ratio between the change in stocks and the rate of production ($\Delta S/J$) will decline rapidly for about 120 years before reaching 0 when the rate of production is exactly balanced by the rate of oxidation ((B) dashed line).

252 (Eq. (1)). The rate of production is a constant J . The change
 253 in the stock in year t will be described by Eq. (2). The solid
 254 line in Fig. 2A shows that the stock will increase for about
 255 6 years after which it will remain constant indefinitely. In
 256 the simple approach described by Marland and Rotty (1984)
 257 and the IPCC (1997), we would say that for every year after
 258 year 6, there is no increase in carbon stocks in the product,
 259 the rate of oxidation in any given year is equivalent to the
 260 rate of production, and there is no product sent to long-term
 261 storage. A national inventory would show that the amount

oxidized is equal to the amount produced for all years after 262
 263 after the 6th year. For years up to year 6, we could describe
 264 the increase in carbon stocks as a fraction of J ($\Delta S/J$ in
 265 Fig. 2B, solid line), but the fraction would change rapidly
 266 with time as the steady state level of the carbon stock (about
 267 1.4 times the annual rate of production, see Fig. 2A) was
 268 approached.

$$B(t) = kS(t) = \left(\frac{\ln 2}{\tau_{1/2}} \right) S(t) \quad (1)$$

270 where k is the rate coefficient for the oxidation and $\tau_{1/2}$ the
271 half-life of the product.

$$272 \frac{dS}{dt} = J(t) - B(t) = J(t) - \left(\frac{\ln 2}{\tau_{1/2}}\right) S(t) \quad (2)$$

273 In the following sections, we explore circumstances where
274 products have longer half-lives and/or the rate of production,
275 J is not constant. We seek simple rules to characterize the
276 rate of change in carbon stocks as a function of the rates
277 of production and/or oxidation, and that may be useful for
278 carbon-containing products in use on earth. After looking
279 at several hypothetical situations, we examine real data for
280 production of three products and examine the implications
281 for estimating greenhouse gas emissions.

282 3.2. Constant production

283 With production constant and a short half-life for the prod-
284 uct, the stock of product was seen (Fig. 2, solid line) to soon
285 reach steady state, with no further increase in the stock of
286 product. The time to steady state, however, increases with
287 the half-life of the product. Consider the same circumstance
288 as in Fig. 2 (solid line), except that the half-life for oxida-
289 tion of the product in use is 20 years. In this case, the stock
290 of product will increase for some 120 years, and then will
291 remain constant, so long as J remains constant (Fig. 2A,
292 dashed line). Fig. 2B (dashed line) shows that the annual in-
293 crease in the stock (ΔS) drops from essentially 1.0 times J
294 in the first year to 0.1 J around year 70 and to near zero by
295 year 120. The annual increase in stocks (ΔS) could not be
296 accurately described as a simple fraction of the rate of pro-
297 duction (J) without knowing the time since production began
298 and the half-life. Although one might reasonably note that
299 $\Delta S/J$ could be approximated as 0.05 ± 0.05 after year 70,
300 this approximation does not accurately represent the first 70
301 years of production; years during which stocks grow rapidly
302 toward eventual stabilization at about 29 times J . To gener-
303 alize, we can show that the level of carbon stocks actually
304 stabilizes at a value equal to $\tau_{1/2}/\ln 2$. For our purposes, we
305 define this steady state to have been reached when the rate
306 of stock change is only 0.01 times the production rate per
307 half-life, i.e. $\Delta S/J = 0.01/\tau_{1/2}$. This provides a useful def-
308 inition of steady state that is appropriate even at very long
309 half-lives, and steady state occurs uniformly after 6.11 (ap-
310 proximately 6) half-lives. Table 2 shows the time required to
311 reach a steady state stock for different values of the half-life.

312 From this simple illustration, we are able to demonstrate
313 the contention of Marland and Rotty (1984) that at constant
314 rates of production and sufficiently long time scales (with
315 respect to the half-life of the products under consideration),
316 the annual rate of production will come into balance with the
317 annual rate of oxidation, so that there is no annual increase in
318 the stock of products. For times shorter than approximately
319 six half-lives, the stock will increase each year, even with a
320 constant rate of production. The annual increase in stocks is
321 not, however, accurately described as a simple fraction of the

Table 2

Approximate time required to achieve a steady state stock of products,
and the amount of that stock, when production is constant and decay is
first order; with different values for the product half-life

Rate of production (mass units per year)	Half-life of product (years)	Steady state stock of product (mass units)	Time to approximate steady state (years)
1	1	1.4	6
1	5	7.2	30
1	10	14.4	60
1	20	28.9	120
1	100	144.3	600

annual rate of production. In the early years of production, 322
an amount equal to a large fraction of the annual production 323
will add to the stock of products, but as the time approaches 324
about six half-lives, the annual increase in the product stock 325
will approach zero. The stock will stabilize at about 1.4 326
times the annual rate of production times the half-life of the 327
product (actually $(1/\ln 2)$ times the half-life). The critical 328
parameter for describing the annual increase in stocks is the 329
ratio between elapsed time and the product half-life. 330

4. Exponentially growing production 331

In an expanding global economy, we observe that the rate 332
of production of many goods and services is not constant, as 333
in the examples of Fig. 2, but is growing. Global population, 334
for example, is one parameter driving production and it has 335
been growing exponentially at a rate that is now about 1.3% 336
per year (World Resources Institute, 2000). We consider the 337
relationship between the rate of production and the stock of 338
a wood or petrochemical product, and we consider first the 339
case for exponential growth in production. For exponential 340
growth, the rate of production is described by Eq. (3). 341

$$J(t) = J(t-1)e^{rt} \quad (3) \quad 342$$

where $J(0) = 1$, and r is the exponential growth rate. 343

We continue to assume that product oxidation is a first 344
order decay, i.e. that the rate of decay is proportional to 345
the amount of product present (Eq. (1)). We look first at 346
a case with a low growth rate, 2% per year ($r = 0.02$), 347
and a short product life, half-life = 1 year. The solid line 348
in Fig. 3 shows that the stock (1) grows rapidly over the 349
first 5 years (Fig. 3A); (2) continues to grow through time 350
(Fig. 3A); and (3) can soon be described as a linear function 351
of the production rate (Fig. 3B). The change in stock can 352
be described as a simple fraction (about 1% in this case) of 353
the rate of production after about year 6 (Fig. 3C). For the 354
sake of quantitative description, we define a steady state as 355
the point at which the slope $d(\Delta S/J)/dt = 0.01/\tau_{1/2}$. 356

The patterns observed in the solid lines of Fig. 3 are main- 357
tained so long as growth in production is exponential and 358
decay is first order. What changes with the durability of the 359
360
361

360 product is the time required to reach a steady state relation-
 361 ship between stock change and production rate and the frac-
 362 tion of annual production at which this leveling out occurs.
 363 The dashed lines in Fig. 3 show the relationships for 2%
 364 per year growth when the product half-life is 20 years. The
 365 early change in slope in the plot of stock versus time is less
 366 obvious for the dashed line in Fig. 3A than for the solid line

367 because of the slower onset of product decay, and it takes 367
 368 longer to establish a linear relationship between stock and 368
 369 production rate (Fig. 3B, dashed line versus solid line), but 369
 370 by the end of 50 years the system approaches steady state, 370
 371 with the stock growing continually at a rate that is about 371
 372 40% of the rate of production (Fig. 3C, dashed line). The 372
 longer the half-life of the products, the longer it takes to

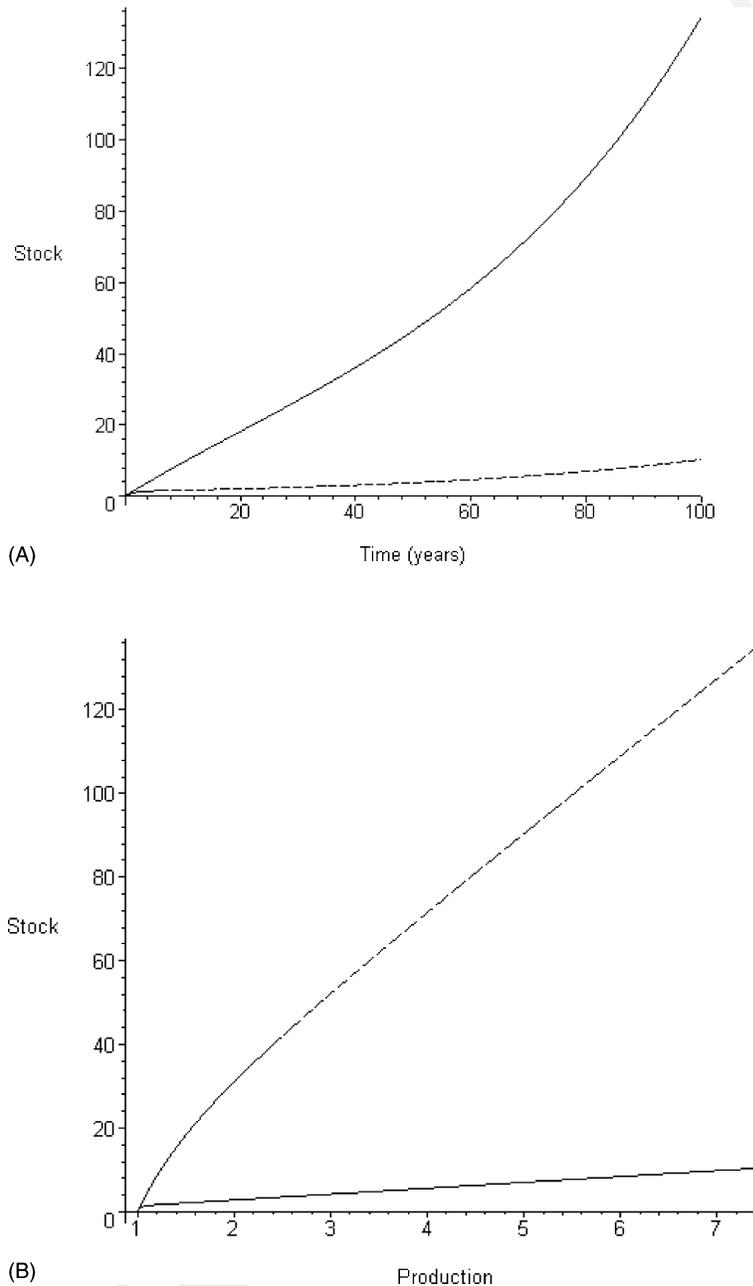


Fig. 3. When the rate of production of a product is growing at 2% per year and decay is first order with a half-life of 1 year (solid lines), the stock will increase continually, but after the first 6 years or so, grows at a rate that is a constant fraction of the production rate. Fig. 3A (solid line) shows the stock growing as a function of time. Fig. 3B (solid line) shows that the relationship between stock and production rate is linear after the early settling in time, and Fig. 3C (solid line) shows the ratio of the annual increase in stocks to the annual production rate. When the rate of production of a product is growing at 2% per year and decay is first order with a half-life of 20 years (dashed lines), the stock will increase continually with time (Fig. 3A, dashed line). After the first 50 years, stocks are growing linearly as a function of the rate of production (Fig. 3B, dashed line) and the annual stock change is roughly 40% of the annual rate of production (Fig. 3C, dashed line).

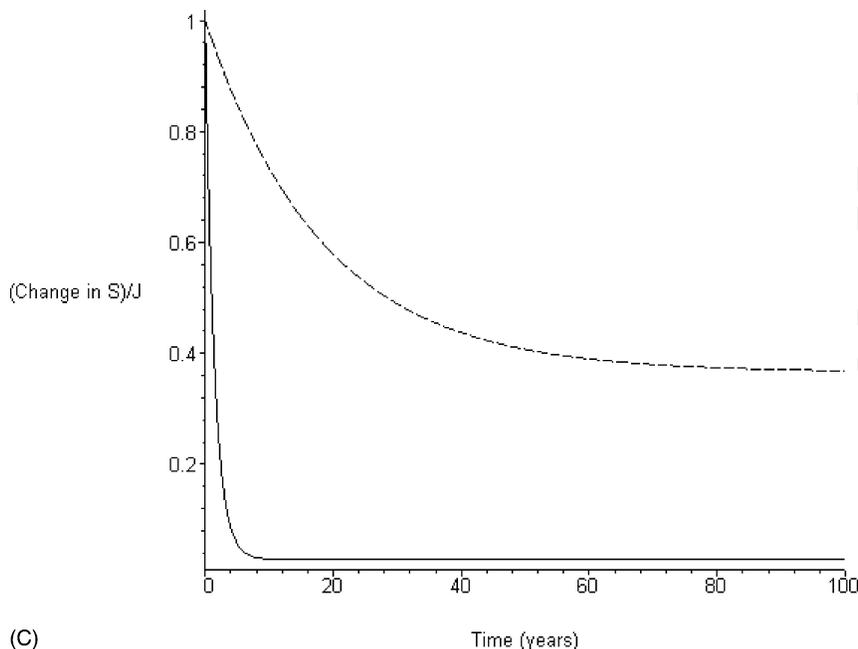


Fig. 3. (Continued).

373 achieve the steady state of $\Delta S/J$ and the higher the fraction
374 of production at which it stabilizes.

375 Longer product half-lives lead to achieving balance be-
376 tween production and oxidation at higher values of $\Delta S/J$.
377 Higher growth rates for production also lead to achieving
378 balance with higher values of $\Delta S/J$. We can, in fact, general-
379 ize these relationships and solve algebraically for the steady
380 state value of stock change versus production rate as a func-
381 tion of growth rate and half-life (Eq. (4)), recognizing that
382 the time required to reach this steady state also varies with
383 growth rate and half-life.

$$384 \quad \frac{\Delta S}{J} = \frac{r}{r+k} = \frac{1}{1+m} \quad (4)$$

385 where $k = \ln 2/\tau_{1/2}$ as in Eq. (1), r is the exponential growth
386 rate from Eq. (3) and m is defined as the ratio between
387 the doubling time of production ($\ln 2/r$) and the half-life
388 of the product. Eq. (4) provides a simple relationship be-
389 tween the steady state value of $\Delta S/J$ and the rates of pro-
390 duction and oxidation of the product, and it emphasizes that
391 we need to know the rates of both production and oxida-
392 tion.

393 Fig. 4 shows how the ratio of stock change to production
394 rate changes with the exponential growth rate of production
395 and the half-life of the product. The figure ignores the early
396 “settling in” period during which a larger fraction of pro-
397 duction accumulates in the growing stock of product. Once
398 this initial period of high growth is passed, the annual in-
399 crease in stocks can be represented as a constant fraction of
400 the rate of production, as described in Eq. (4). The IPCC
401 (1997) suggestion that 80% of the carbon in LPG used for
402 feedstocks is stored in long-lived products, as an example,

could thus be appropriate if LPG production is increasing at 403
2% per year and the products have a half-life of 139 years, 404
if LPG production is growing at 5% per year and products 405
have a half-life of 55 years, or if LPG production is grow- 406
ing at 10% per year and products have a half-life of 28 407
years. We do not have an estimate of the half-life for these 408
products. 409

The time required to achieve a constant ratio between 410
stock change and production rate also varies with both the 411

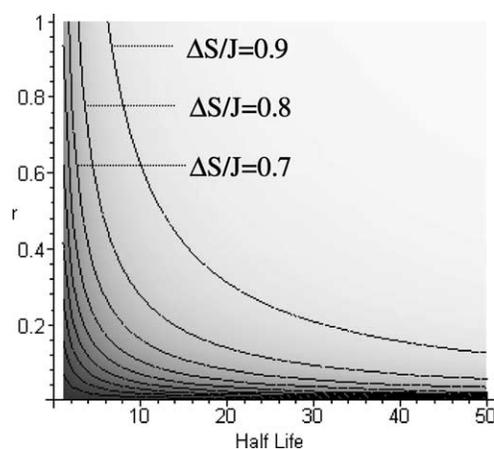


Fig. 4. When production is increasing exponentially and decay is first
order, the ratio of stock change to growth rate ($\Delta S/J$) depends on both the
growth rate of production and the half-life of the product. $\Delta S/J$ increases
with both increasing growth rate and increasing half-life. Plotted here are
the contoured values of $\Delta S/J$, with a contour interval of 0.1 and the last
three contours labeled on the figure. These values are achieved only after
an extended period of growth in stocks and establishment of a steady
state relationship between the rates of growth and decay (see Fig. 5).

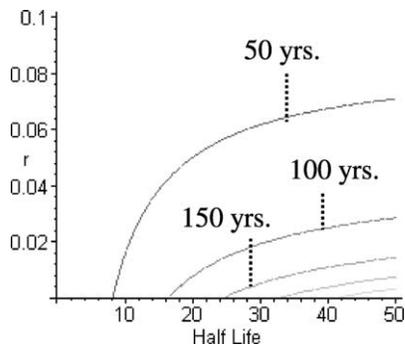


Fig. 5. With exponential growth in production and first order decay of a product, the annual increase in stocks will eventually become a constant fraction of the annual rate of production. The time required to reach this steady state relationship depends on the half-life of the product and the rate of growth in production (see Eq. (5)). Here we show the time required to achieve steady state in $\Delta S/J$ (defined as the point at which $d(\Delta S/J)/dt = 0.01/\tau_{1/2}$) as a function of half-life and the growth rate of production.

412 production rate and the product half-life and we can solve
 413 for the time to steady state as a function of r and k (Eq. (5)).
 414 Fig. 5 shows how time to steady state varies with half-life
 415 and the exponential growth rate r .

$$416 T_{ss} = 4.24 \left(\frac{1}{r + k} \right) \quad (5)$$

417 where T_{ss} is the time required for $d(\Delta S/J)/dt$ to reach
 418 $0.01/\tau_{1/2}$.

419 In addition to the simple production and decay scenarios
 420 considered so far, there are a wide variety of mixed scenar-
 421 ios that one might envision to represent the use and fate of
 422 petrochemical and wood products. As examples: (1) a prod-
 423 uct could be used in two ways, each with its own half-life;
 424 (2) a product could be oxidized by two different processes,
 425 each with its own process half-life; (3) a product could be
 426 recycled or converted to a secondary product which subse-
 427 quently oxidized; or (4) a product could be oxidized to a lim-
 428 ited extent during use and then discarded to waste processing
 429 where oxidation continued at a different rate. In every such
 430 case the aggregate stock of products will grow continuously
 431 at a rate that can be described as a constant fraction of the
 432 primary production rate—so long as the rate of production
 433 of the product or products is growing exponentially, the rate
 434 of each product decay is a first order function of the size of
 435 its stock, and the time is sufficiently great with respect to
 436 the product half-life that steady state has been achieved. The
 437 time required to reach steady state in $\Delta S/J$ and the value of
 438 this steady state $\Delta S/J$ will be unique to the details of each
 439 case, but the basic relationships illustrated above will pre-
 440 vail. To illustrate this for some of the more complex scenar-
 441 ios, Fig. 6A shows $\Delta S/J$ over time for a scenario with
 442 product recycle and Fig. 6B shows the same for a scenario
 443 with production of two independent products with different
 444 half-lives.

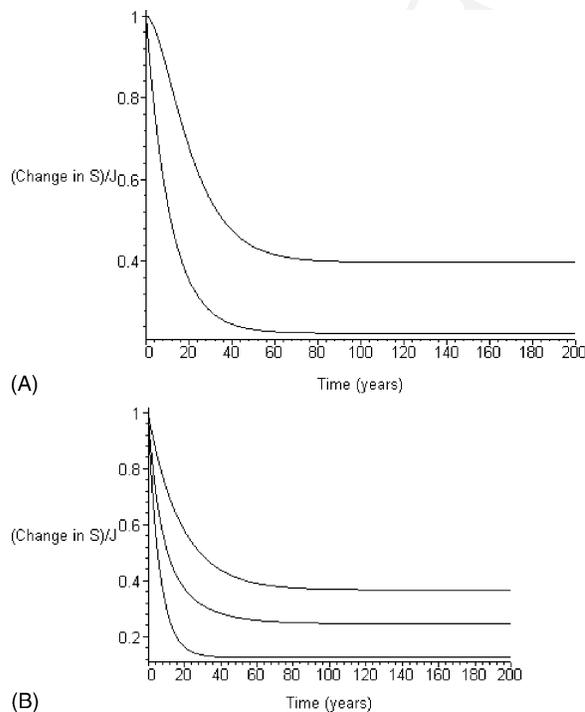


Fig. 6. (A) shows the annual ratio of stock change to production ($\Delta S/J$) when production is increasing at 2% per year, the product has a useful half-life of 10 years, 100% of the product is recycled through a second usage, and the product is discarded and oxidized following its second use (upper curve). For comparison, (A) also shows (lower curve) values of $\Delta S/J$ that would apply if the product were discarded after a single usage. (B) shows $\Delta S/J$ for a product that is used in two ways, one with a half-life of 5 years and one with a half-life of 20 years (center curve). Production is still assumed to be growing at 2% per year. For comparison, (B) also shows the values of $\Delta S/J$ for a single product with a half-life of 5 years (lower curve) or 20 years (upper curve).

4.1. Linearly growing production

445 Whereas the ratio of stock change to production rate ap-
 446 proaches a constant value when growth is exponential, this
 447 is not the case for other forms of growth. We illustrate with
 448 the case when growth is linear. When production grows lin-
 449 early, each year's production yields some growth in stocks,
 450 but the growth in stocks will be a continually declining frac-
 451 tion of production and never approaches a constant relation-
 452 ship with the rate of production. Fig. 7 shows the case where
 453 production is 1 unit in the first year and increases by 1 unit
 454 per year, while oxidation of the product is again by first or-
 455 der decay with a half-life of 1 year. 456

457 Comparison of Fig. 7 with a case that is identical except
 458 for a longer half-life, now 20 years (Fig. 8), shows that at
 459 a longer half-life, the stock builds up faster and the annual
 460 growth in stocks is a larger fraction of production, but the
 461 basic pattern is unchanged. The critical feature for our inter-
 462 est here is that for linear growth there is never a point
 463 at which the increase in stocks can be accurately repre-
 464 sented as a simple fraction of annual production. The same
 465 can be demonstrated for any other pattern of growth that is
 466

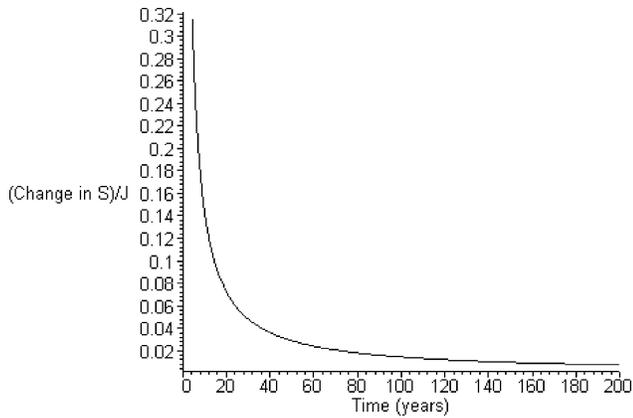
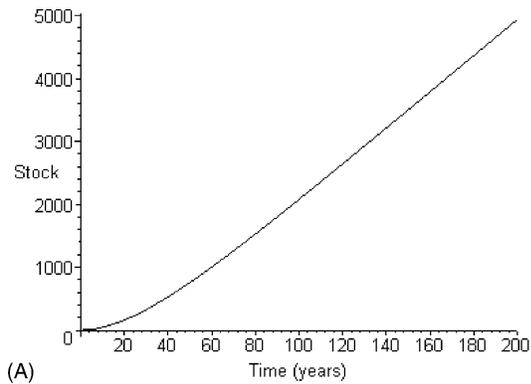
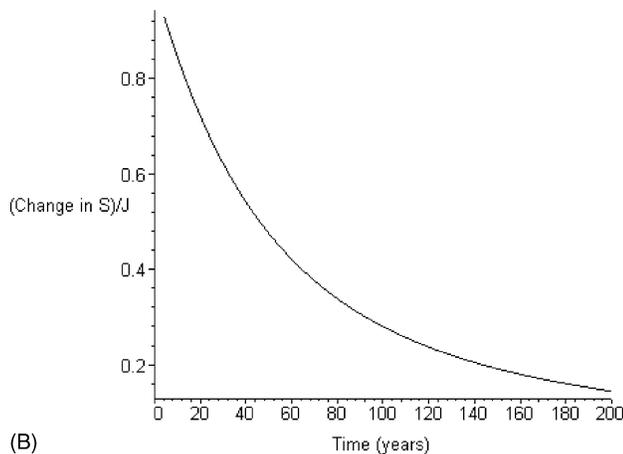


Fig. 7. With production at 1 unit in the first year and increasing linearly by 1 unit per year, and first order decay with a half-life of 1 year, the stock will grow continuously as a function of time (see, for example, Fig. 8A). However, $\Delta S/J$ declines continuously over time and does not approach a constant value, as it would with exponential growth.

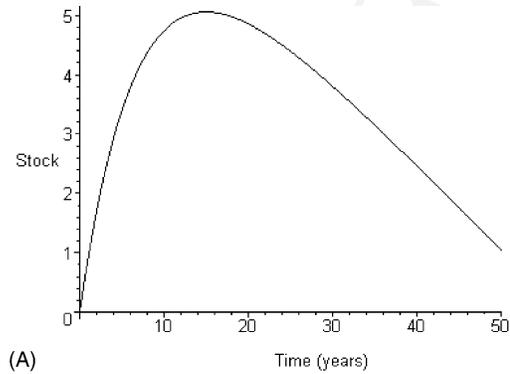


(A)

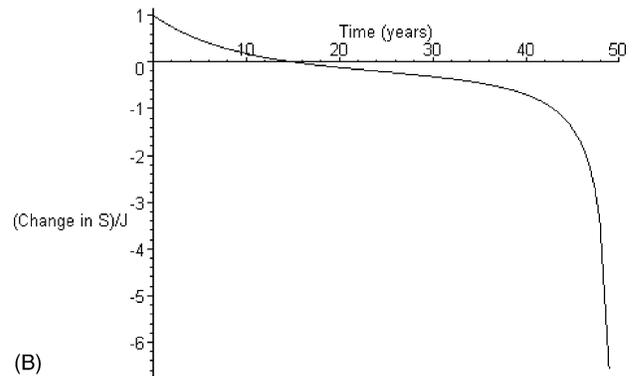


(B)

Fig. 8. With production at 1 unit in the first year and increasing linearly by 1 unit per year, and first order decay with a half-life of 20 years, the stock will grow continuously as a function of time (A) (and identically as a function of the annual rate of production, which is a linear function of time). However, $\Delta S/J$ declines continuously over time and does not approach a constant value (B), as it does with exponential growth (compare Fig. 3C, dashed line). With lower decay rates, the stocks will build-up much more than in the case of Fig. 7, but $\Delta S/J$ will still decline continuously toward zero.



(A)



(B)

Fig. 9. For declining production of a durable product, it is possible to observe either increasing or decreasing product stocks, depending on the time with respect to the onset of decline (A). The value of $\Delta S/J$ can be positive or negative and changes significantly over time (B). In the example shown here, production starts at 1 unit per year and declines linearly to zero over 50 years. We assume that the product undergoes first order decay with a half-life of 5 years.

less than exponential. We could, of course, choose a point at which $\Delta S/J$ approaches within some chosen increment of zero.

4.2. Declining production

The cases examined so far have involved production that is constant or increasing. As an illustration of the effect of declining production, we consider the case where production is at 1 unit in the first year and then declines in a linear way, going to zero after 50 years (Fig. 9). If the half-life of the product is taken to be 5 years, the stock of product will build-up for 15 years, until the oxidation rate exceeds the production rate (Fig. 9A). After this 15th year, the stock will begin to decline and $\Delta S/J$ will become negative (Fig. 9B). If we choose a longer half-life, the maximum stock accumulation will be larger and the point at which $\Delta S/J$ goes negative will move further out in time. In the current context, it is notable that although there is no simple factor to describe the relationship between production and the increase in stocks, there is an annual net increase in the stocks that continues well into the period of declining production. There is a longer period where the annual change in the stock of

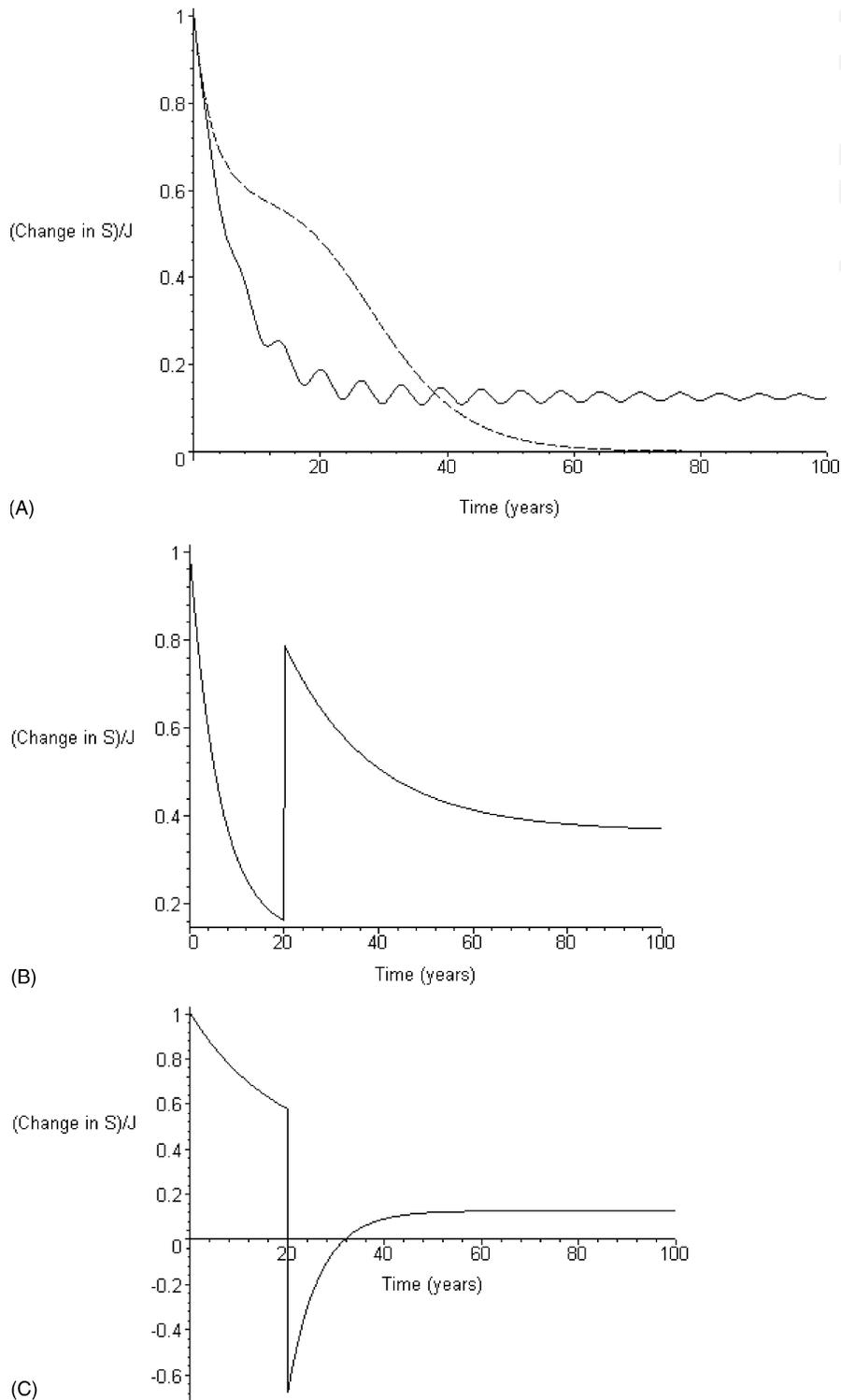


Fig. 10. The pattern of $\Delta S/J$, the change in product stocks as a function of the production rate, when there is a change in the pattern of either production (A) over time, or of product oxidation (C) and (D) over time. In (A) (dashed line) production is assumed to be growing along a sigmoidal curve with the point of inflection at 20 years and an upper asymptote at 2 units of production per year. Oxidation is a first order decay with a half-life of 20 years. In (A) (solid line), production is increasing at 2% per year with variability superimposed by adding $0.05 \sin t$ to the exponential growth term. Products are assumed to have a half-life of 10 years. In (B), production is assumed to be growing at 2% per year and the half-life of products changes abruptly from 5 to 20 years in year 20. In (C), production is assumed to be growing at 2% per year and the half-life of products changes abruptly from 20 years to 5 years in year 20.

487 products is negative, even though additional product is con-
488 tinuing to be produced.

489 4.3. Changing rates or patterns

490 All of the scenarios described thus far have assumed that
491 we can identify patterns that describe production and oxida-
492 tion as continuous functions of time. In fact, we can expect
493 that there will often be changes with time: a leveling off
494 of growth, for example, or a change in the way a product
495 is used or disposed of, so that the half-life of the product
496 changes notably. We might also encounter situations where
497 the rate of production varies significantly from year-to-year,
498 whether in a regular or “noisy” way. To show that these sit-
499 uations yield results that conform to the patterns described
500 above, and yet to recognize the kinds of dislocations that
501 would need to be considered in emissions inventories, we
502 describe briefly four scenarios in which there is a signifi-
503 cant change in either the pattern of production or the pattern
504 of oxidation over time. Fig. 10 illustrates the variation in
505 $\Delta S/J$ over time for two cases with varying production func-
506 tions and two cases with changes over time in the decay
507 function.

508 In Fig. 10A (dashed line), we assume that production
509 can be described with an S-shaped, sigmoidal function,
510 i.e. that production initially approximates exponential
511 growth but eventually passes through an inflection point
512 and then asymptotically approaches some constant level.
513 The graph shows that $\Delta S/J$ starts toward the asymptote
514 associated with exponential growth but transitions toward
515 zero as the rate of growth in production approaches zero.
516 To examine the effect of noise or variability in the pro-
517 duction function, in Fig. 10A (solid line), we have taken
518 an exponential growth curve with 2% per year growth and
519 superimposed a sine wave (i.e. added $0.05 \sin(t)$ to the ex-
520 ponential growth term). The plot of $\Delta S/J$ shows that our
521 expectation of an eventual constant value for $\Delta S/J$ is main-
522 tained, albeit with noise from the noisy input signal super-
523 imposed.

524 A change in the way products are used or disposed of, such
525 as the conversion from waste dumps to modern landfills,
526 might be represented by a change in the half-life of products.
527 Fig. 10B illustrates the changing value of $\Delta S/J$ when the
528 half-life of products changes from 5 to 20 years during year
529 20. The figure reflects a large build-up in product stocks fol-
530 lowing the stepwise increase in product half-life. In related
531 fashion, Fig. 10C reflects a very rapid draw down in product
532 stocks following an abrupt change in product half-life from
533 20 to 5 years. When the half-life of the product decreases
534 dramatically in year 20, the oxidation of products exceeds
535 the rate of production for years 20–32. Fig. 10B and C show
536 the eventual stabilization of production and oxidation at con-
537 stant $\Delta S/J$. These two figures illustrate that abrupt changes
538 in the use of products could have very dramatic short-term
539 effects on the best estimate of carbon storage in durable
540 products.

4.4. Alternate decay functions and spread-sheet analyses

541 We have constructed the scenarios above using the as-
542 sumption of first order exponential decay because this is
543 among the simplest situations to treat mathematically and
544 because we wanted to explore the possibilities and implica-
545 tions of using the simple assumption of constant $\Delta S/J$. There
546 are other decay schemes that should be explored and which
547 might be more realistic representations of the oxidation of
548 many durable products. One approach is to distribute prod-
549 uct oxidation over many years according to the probability in
550 each year that the product will oxidize in that year. A poten-
551 tially useful function, a function often used to describe time
552 to failure, is the gamma function. A typical gamma function
553 has the form shown in Fig. 11. This is a continuous probabili-
554 ty distribution that can be fitted to very closely resemble the
555 3-segment curve that Row and Phelps (1996) use to describe
556 the life expectancy of wood products. Other, more general-
557 ized, gamma functions can be fit to the decay pattern seen in
558 various products. The gamma function would describe the
559 probability of oxidation as a function of time since produc-
560 tion and would have a maximum probability corresponding
561 to the nodal value of the product life, decreasing to zero
562 to either side. The gamma function would then be used as
563 the kernel of an integral to describe the distribution of stock
564 produced at different times in the past that is oxidized at
565 the current time. The general form of the model, including
566 exponential growth of production, is given in Eq. (6).
567
568

$$\frac{dS}{dt} = e^{rt} - \int \Gamma(x-t)S(x-t) dx, \quad \text{from } x = 0 \text{ to } t \quad (6)$$

569
570 By contrast, for first order exponential decay, the entire
571 stock is treated equally regardless whether it was produced
572 last year or 40 years ago. Oxidation is simply a proportion
573 of the total stock.

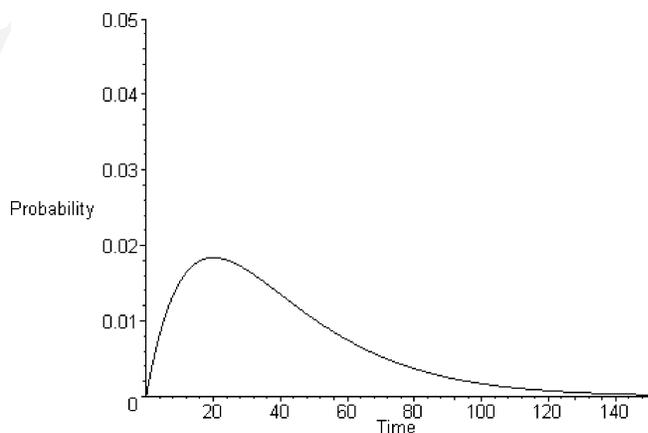


Fig. 11. A typical gamma function that might be used to describe the probability of oxidation of durable products. In this example, the products have a modal lifetime of 20 years and the probability of oxidation at greater or lesser times is described by the curve. The area under the curve is equal to 1.

574 Although we leave detailed mathematical examination of
575 the gamma function for future inquiry, we note that so long
576 as the right-hand side of the curve of the gamma function
577 is basically an exponential decay, many of the qualitative
578 aspects of the results discussed above for first order decay
579 will prevail, particularly for asymptotic behavior. Use of a
580 Γ function, or other probability distribution, to represent
581 product oxidation could also mesh well with the discrete na-
582 ture of collected data. The probability distribution could be
583 incorporated into look-up tables to estimate the fraction of
584 product oxidized in each year following initial production.
585 This suggests a year-by-year, discrete tabulation of produc-
586 tion and oxidation using spread-sheet analyses. Spread-sheet
587 analyses would also accommodate production functions that
588 could not be well described with exponential or other simple
589 growth curves. It is likely that this sort of discrete analysis
590 would provide the most accurate estimates of CO₂ emissions
591 over time, if time-series data were available on production
592 and an accurate representation of the probability of oxida-
593 tion over time could be constructed. In fact, this is exactly
594 the kind of spread-sheet analysis of wood product oxidation
595 carried out in many modeling exercises (see, for example,
596 [Schlamadinger and Marland, 1996](#)). However, this type of
597 analysis is very data intensive and is what we have tried to
598 avoid by looking for simple, functional relationships among
599 production, oxidation, and stock changes.

600 5. Three real examples

601 Having discussed the evolution of $\Delta S/J$ that might be
602 observed for hypothetical patterns of product growth and
603 decay, we examine three cases with real data on the rate
604 of production over time. We have chosen to look at data
605 for one petrochemical product and one forest product and
606 we have selected data for two countries where the recent
607 patterns of growth are very different. Data on lubricants
608 for the US and China are from the United Nations Energy
609 Statistics Office ([UN, 2001](#)) and data on lumber are from the
610 Statistical Abstract of the US ([US Census Bureau, 2001](#)).

611 Note that these data sets provide useful perspective for
612 analysis, but they also address some of [Gielen's \(1997\)](#) con-
613 cerns about the reporting of emissions and treatment of prod-
614 ucts that are traded in international commerce. The lumber
615 statistics are not production statistics, but are for US con-
616 sumption and include consideration of imports and exports.
617 The lubricant data are also for consumption and have been
618 calculated as domestic production plus imports minus ex-
619 ports and minus any change of stocks in storage. The data
620 do not include consideration of trade in final products, i.e.
621 lumber as furniture or lubricants in engines.

622 We do not have data on the rate of oxidation of these
623 products. We assume that both are oxidized as a first order
624 decay process, i.e. that the rate of decay is a function of the
625 amount of stock in use. We do need to estimate a half-life
626 for each product. [Buchanan and Levine \(1999\)](#) use 1 year

as the average life for fuel wood and waste, 3 years for
627 paper products, and 40 years for solid wood products. For
628 comparison, [Skog and Nicholson \(1998\)](#) consider durable
629 wood and paper products under 11 product categories, with
630 half-lives ranging from 1 year for most paper products to
631 100 years for post-1980 single family homes. Recognizing
632 the difference between the average life and the half-life, we
633 take 40 years as the half-life for solid wood products derived
634 from lumber. For lubricants, we assume that the half-life will
635 be in the range of 2–5 years and use both of these values
636 in the analysis. The half-life of lubricants could be notably
637 different in the US and China as patterns of use, re-use, and
638 disposal differ. The half-life could also be changing with
639 time as patterns of recycle and disposal change.
640

641 The data on consumption of lubricants from 1970 to 1998
642 in the US have considerable year-to-year variability and can
643 be fit almost equally as well with a linear or an exponen-
644 tial fit. Because we know that $\Delta S/J$ will behave best when
645 growing production can be modeled with an exponential, we
646 choose the best exponential fit. The growth rate is low with
647 $r = 0.0021 \text{ year}^{-1}$. As the assumed half-life increases from
648 2 to 5 years, the steady state value of $\Delta S/J$ increases from
649 0.006 to 0.014 and the time required to reach this steady
650 state increases from approximately 12 to 30 years. The bot-
651 tom line here is that (assuming we have the right range for
652 the half-life) lubricant stocks in the US should have reached
653 a steady state relationship between ΔS and J and the annual
654 increase in stocks should be on the order of 1% of annual
655 production.

656 Data for lubricant consumption in China from 1978 to
657 1998 are less regular, but the best fit exponential can be
658 found. The growth rate has $r = 0.051 \text{ year}^{-1}$. As the as-
659 sumed half-life increases from 2 to 5 years, the steady state
660 value of $\Delta S/J$ for China increases from 0.13 to 0.27 and the
661 time required to reach this steady state increases from ap-
662 proximately 11 to 22 years. Again, assuming that we have
663 correctly bracketed the half-life, the pattern of growth in use
664 of lubricants in China has been long enough that the steady
665 state relationship between ΔS and J should have been estab-
666 lished, and the stock of lubricants in place in China should
667 be growing annually at 13–27% of the annual rate of pro-
668 duction. Comparison of these values for $\Delta S/J$ with those in
669 [Table 1](#) suggests that if the US and China were using the
670 values suggested by the US EPA and the IPCC, respectively,
671 they would be using values that are on the high side but of
672 the correct order of magnitude, and would be properly ac-
673 knowledging that the value should be higher for China than
674 for the US.

675 Data for lumber consumption in the US are plotted in
676 [Fig. 12](#) along with the best exponential fit and the corre-
677 sponding values of $\Delta S/J$. With an assumed half-life of 40
678 years, and the best fit exponential growth rate $r = 0.0175$,
679 the value of $\Delta S/J$ will approach an asymptote at 0.502 (see
680 [Fig. 12B](#)). The time required to reach this steady state would
681 be 120 years. To the extent that lumber consumption in the
682 US is accurately characterized by exponential growth and

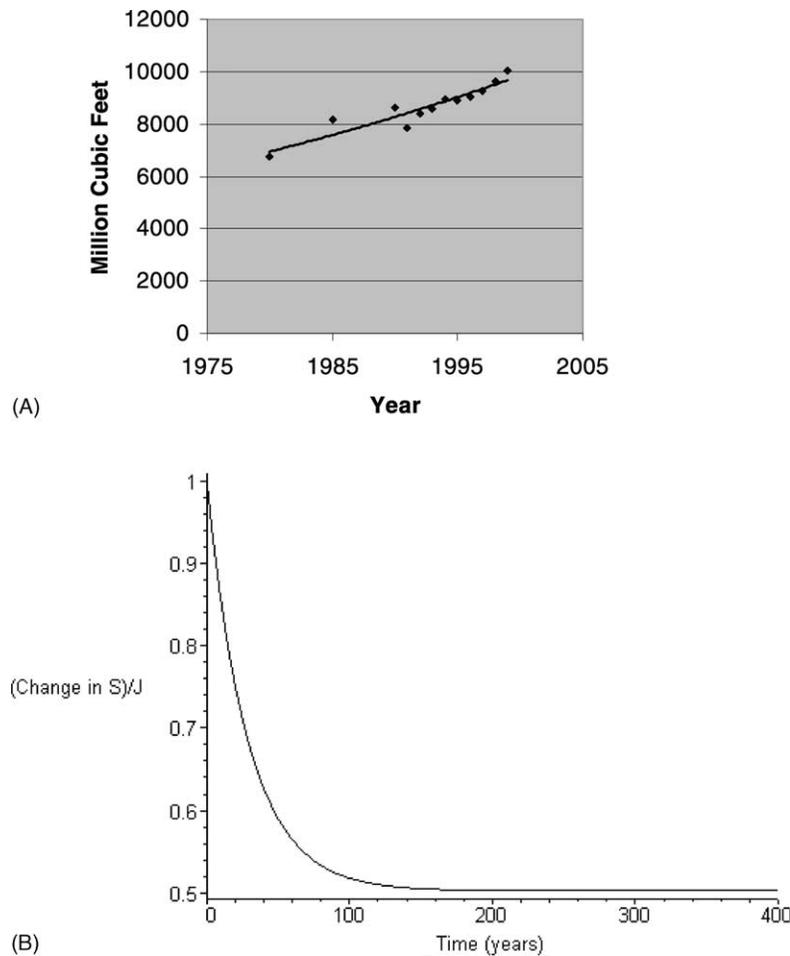


Fig. 12. Data on consumption of lumber in the US are shown with the best fit exponential. The best fit is at $y = 7 \times 10^{-12} e^{0.0175t}$ with $R^2 = 0.8642$ (A). Using this production function, and assuming a half-life of 40 years for all products, yields values for the ratio of the increase in product stocks to the annual rate of production ($\Delta S/J$) shown in (B). Values of $\Delta S/J$ show that after about 120 years, the annual increase in stocks will be constant at 0.502 times the annual production (data are from US Census Bureau, 2001; data are shown in the originally reported units, where $1 \text{ ft}^3 = 0.028 \text{ m}^3$).

683 an unchanging half-life of 40 years, we would conclude that
 684 there is an increasing stock of products that is of an amount
 685 equivalent to approximately half of the current year's pro-
 686 duction.

687 6. Conclusions

688 The IPCC methodology (IPCC, 1997), based on earlier
 689 work by Marland and Rotty (1984), assumes that we can de-
 690 scribe the annual increase in stocks (ΔS) of durable organic
 691 products as a constant multiple of the annual rate of produc-
 692 tion (J). We have shown that $\Delta S/J$ is a constant only when
 693 J can be characterized as an exponential function of time,
 694 the product oxidizes by a first order decay process, and time
 695 is long with respect to the half-life of the product. The as-
 696 sumption of constant $\Delta S/J$ may provide a useful estimate of
 697 the rate at which carbon is stored in durable products when
 698 we want to estimate the change in stocks (ΔS) with simple
 699 methods and limited data.

700 However, the IPCC adopts a single value for $\Delta S/J$ and we
 701 have shown that the value should depend on both the half-life
 702 of product oxidation and the exponent of the exponential
 703 growth in production. Our conclusion is that, although the
 704 demands on data remain modest, the use of a constant factor
 705 to estimate the change in stocks from current production
 706 requires some knowledge on the time history of production
 707 and an estimate of the product half-life. Use of the same
 708 value of $\Delta S/J$ for all countries or all producers is, therefore,
 709 not appropriate. Different rates of increase in production
 710 can yield vastly different rates of increase in stocks and
 711 poor estimates of the production function can lead to poor
 712 estimates of the increase in stocks.

713 It is clear that the steady state value of $\Delta S/J$ will be differ-
 714 ent in different places, but it can also be different at different
 715 times in one place. As pointed out by Skog and Nicholson
 716 (1998) for forest products, over time we can expect changes
 717 in production methods, the distribution of products, product
 718 half-lives, product recycle, etc. With proper recognition of
 719 historic patterns these changes produce predictable changes

720 in $\Delta S/J$ and can be accommodated in emissions inventories
721 over time.

722 Because the value of $\Delta S/J$ behaves best when J can be
723 described with an exponential function, it seems appropri-
724 ate to select an exponential fit for the history of production
725 whenever appropriate. For all other circumstances it may be
726 necessary to adopt discrete accounting, via spread-sheet for-
727 mats, to convert historic production data and our best under-
728 standing of the probability distribution of product oxidation
729 into estimates of the net increase in product stocks. In ei-
730 ther case, it is clear that separating products into short- and
731 long-lived products, with a demarcation at 20 years (or at any
732 other age), fails to recognize that there can be a substantial
733 build-up of stocks for products with quite short half-lives.

734 We note that the simple approach pursued here is not
735 in conflict with the detailed statistical treatments being de-
736 scribed by [Gielen \(1997\)](#) and [Gielen and Patel \(1999\)](#). The
737 more product and sectoral definition that can be achieved,
738 the better we are likely to be able to describe the rates of
739 production and oxidation. The approach for estimating of
740 CO₂ emissions that is described here can be applied to data
741 at virtually any level of aggregation, depending on the rich-
742 ness of the data bases available.

743 Whether the interest is for geochemical or political pur-
744 poses, an accurate estimate of CO₂ emissions to the atmo-
745 sphere needs to confront the very large amount of carbon
746 stored in durable petrochemical and forest products. The
747 methodology proposed by the [IPCC \(1997\)](#) seems to offer
748 reasonable first estimates so long as we are aware of the
749 limitations and implications of the method and take better
750 advantage of existing understanding on the history of pro-
751 duction and the durability of products. Estimates of CO₂
752 emissions should be improved if estimates are based on all
753 available data on consumption and durability. Better esti-
754 mates seem possible but are likely to be very data intensive.

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762 References

763 Buchanan, A.H., Levine, A.B., 1999. Wood-based building materials and
764 atmospheric carbon emissions. *Environ. Sci. Policy* 2, 427–437.

- Gielen, D.J., 1997. Potential CO₂ emissions in The Netherlands due to
carbon storage in materials and products. *Ambio* 26 (2), 101–106. 765 766
- Gielen, D.J., Patel, M., 1999. The NEAT model non-energy use of GHG
emission accounting tables. In: Proceedings of the first NEU (Non-
Energy Use)-CO₂ Workshop, International Energy Agency, Paris,
France, September 23–24, 1999. 767 768 769 770
- Houghton, R.A., Hackler, J.L., 2001. Carbon flux to the atmosphere
from land-use changes: 1850–1990. Carbon Dioxide Information and
Analysis Center, Oak Ridge National Laboratory, Oak Ridge, TN,
USA, NDP-050 at <http://cdiac.esd.ornl.gov>. 771 772 773 774
- IPCC, 1997. Revised 1996 Guidelines for National Greenhouse Gas
Inventories (three volumes). Intergovernmental Panel of Climate
Change, Hadley Center, Meteorological Office, Bracknell, UK. 775 776 777
- Marland, G., Rotty, R.M., 1984. Carbon dioxide emissions from fossil
fuels: a procedure for estimation and results for 1950–1982. *Tellus*
36B, 232–261. 778 779 780
- Marland, G., Boden, T., Andres, R.J., 2001. Global, regional, and national
CO₂ emissions from fossil-fuel burning, cement production, and gas
flaring: 1751–1998. Carbon Dioxide Information and Analysis Center,
Oak Ridge National Laboratory, Oak Ridge, TN, USA, NDP-030 at
<http://cdiac.esd.ornl.gov>. 781 782 783 784 785
- Okken, P.A., Kram, T., 1990. Calculation of actual CO₂ emissions from
fossil fuels. ECN-RX-90-048. In: Proceedings of the IPCC Preparatory
Workshop, Paris, May 22–23, 1990, ECN, Petten, The Netherlands. 786 787 788
- Row, C., Phelps, R.B., 1996. Wood carbon flows and storage after
timber harvest. In: Sampson, R.N., Hair, D. (Eds.), *Forests and Global
Change*, vol. 2. Forest Management Opportunities for Mitigating
Carbon Emissions. American Forests, Washington, DC, pp. 27–58. 789 790 791 792
- Schlamadinger, B., Marland, G., 1996. The role of forest and bioenergy
strategies in the global carbon cycle. *Biomass Bioenergy* 10, 275–300. 793 794
- Skog, K.E., Nicholson, G.A., 1998. Carbon cycling through wood
products: the role of wood and paper products in carbon sequestration.
Forest Prod. J. 48 (7–8), 75–83. 795 796 797
- United Nations, 2001. 1998 Energy Statistics Yearbook. Department
of Economic and Social Affairs, Statistical Office, United Nations,
NY. 798 799 800
- UNFCCC, 2000. Review of the implementation of commitments and of
other provisions of the convention, UNFCCC guidelines on reporting
and review (Common Reporting Framework). FCCC/CP/1999/7 at
<http://www.unfccc.int>. 801 802 803 804
- United States Census Bureau, 2001. Statistical Abstract of the United
States. US Department of Commerce, Bureau of the Census, Wash-
ington, DC, USA. 805 806 807
- United States Environmental Protection Agency, 2001. Inventory of US
Greenhouse gas emissions and sinks: 1990–1999. EPA 236-R-001,
April, Washington, DC, USA. 808 809 810
- World Resources Institute, 2000. World Resources 2000–2001: People
and Ecosystems, The Fraying Web of Life, Washington, DC, USA. 811 812

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