Rational Research in Environmental Ecology with Consideration of a Sustainable World Economy under Risk

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BIT's 4th Annual International Congress of Environment-2014 (ICE-2014)

Theme: "Clean World, Happy Society"

September 21-23

Qingdao International Convention Center, Qingdao, China

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In order to solve the global warming problem and other environmental and economic problems with global implications, it is necessary that the most relevant and important sustainable management options are well investigated and formulated. Models of biological growth should be developed that describe the production options available over time and space. These models should have relevant scales and be possible to integrate in general optimization models with spatial and dynamic dimensions, where not only the ecological problems are in focus but all relevant economical and technical problems are included. The forests are of particular importance, since they store large amounts of carbon and can produce a sustainable flow of biomass. The latest decades clearly show that detailed deterministic long term planning is irrelevant.

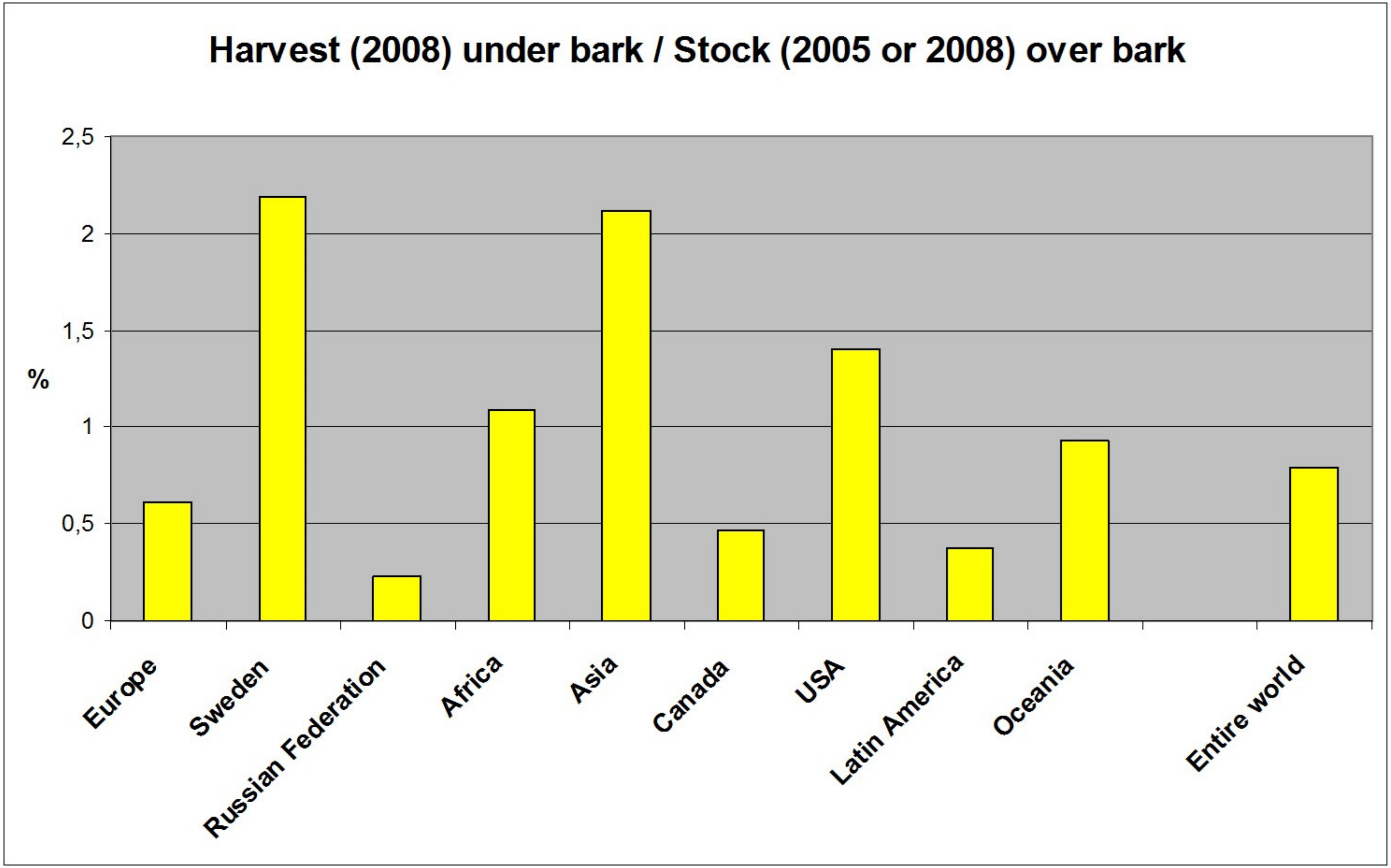
Energy prices, prices of industrial products and environmental problems rapidly change in ways that cannot be perfectly predicted. Research in environmental ecology with consideration of a sustainable world economy should focus on the development of growth models that are useful when stochastic optimal control theory is applied. Since biological production takes considerable time, it is very important to create options to sequentially adjust the production to new relative prices, growth conditions, ecological problems and possible damages caused by parasites, fire or storms. The analysis includes the structure of relevant stochastic optimal control problems and consistent development of research in environmental ecology.

In order to solve the global warming problem and other environmental and economic problems with global implications,

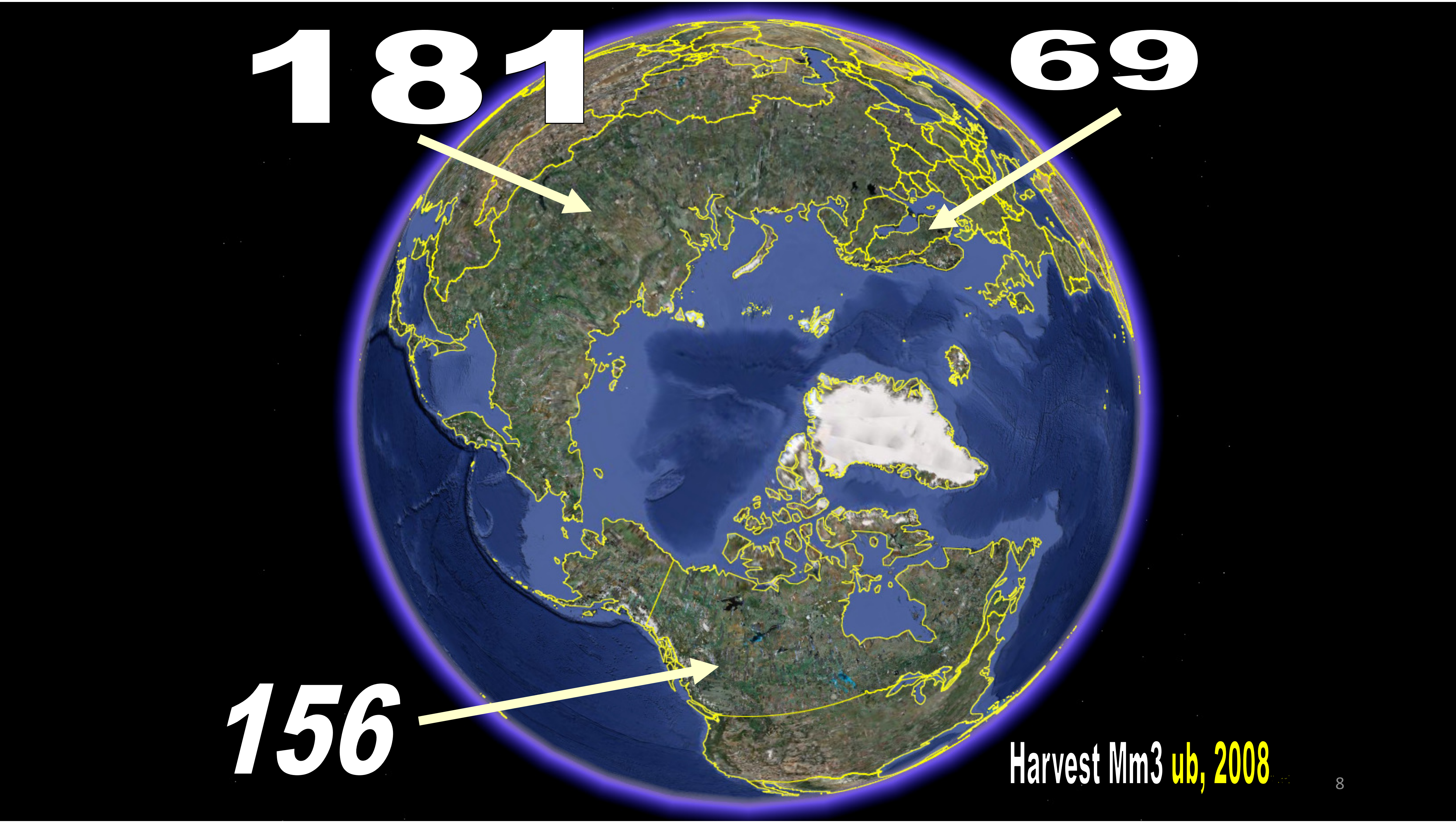
it is necessary that the most relevant and important sustainable management options are well investigated and formulated.

The forests are of particular importance, since they store large amounts of carbon and can produce a sustainable flow of biomass.

The most relevant and important new sustainable management options are found where we presently have very large forest resources with low degrees of utilization.


Harvest (2008) under bark / Stock (2005 or 2008) over bark
%
2,5
2
1,5
1
0,5
0
Europe
Sweden
Russian Federation
Africa
Asia
Canada
USA
Latin America
Oceania
Entire world

Very large forest areas in the north, in particular in Russian Federation and Canada, are covered by more or less natural forests, where trees of different sizes, ages and species, grow together.


181
69
156
Harvest Mm3 ub, 2008

A simple calculation based on official statistics shows that the sustainable forest production potential in Russian Federation is more than 2900 million cubic metres (over bark) per year.

The harvest (year 2008) was only 181 million cubic metres (under bark).

- *http://www.lohmander.com/RuMa09/Lohmander_Presentation.ppt*
- http://www.iiasa.ac.at/Research/FOR/forest_cdrom/english/for_fund_en.html

Table 9

Distribution of forests by relative stocking and site index, 10^3 ha

Subjects of RF, groups of main forest forming species	Total area covered by forest vegetation	Site index														
		I I and higher			I I I			I V			V			Va and lower		
		Distribution of forest area by relative stocking														
		1.0 - 0.8	0.7 - 0.5	0.4 - 0.3	1.0 - 0.8	0.7 - 0.5	0.4 - 0.3	1.0 - 0.8	0.7 - 0.5	0.4 - 0.3	1.0 - 0.8	0.7 - 0.5	0.4 - 0.3	1.0 - 0.8	0.7 - 0.5	0.4 - 0.3
Russian Federation																
Coniferous	504315,8	9194,3	19437,2	2721,7	12405,5	47261,6	12629,7	16327,9	86702,6	31586,3	13148,0	97777,9	51896,8	5193,6	48686,2	49346,5
Hard deciduous	17469,5	434,8	1236,4	127,7	456,0	2177,1	568,2	395,3	2713,4	1067,2	716,1	3467,7	1474,7	294,3	1541,1	799,5
Soft deciduous	123187,1	15071,7	21250,9	2549,0	10477,3	23849,7	4818,0	6086,1	16837,1	3709,9	2524,0	7650,1	1941,1	968,9	3746,3	1707,0
European-Ural part of the Russian Federation																
Coniferous	88090,6	6042,9	10183,0	543,3	3608,9	8719,6	674,5	3256,1	13493,9	1334,1	1625,1	20262,2	3576,5	452,8	9388,7	4929,0
Hard deciduous	5106,5	420,6	1155,7	98,0	348,9	1357,1	110,8	184,6	845,9	90,9	48,5	291,7	38,2	22,3	83,1	10,2
Soft deciduous	47579,8	12041,6	12799,1	561,1	4634,5	7013,1	498,1	1892,0	3363,7	337,1	560,1	1397,5	319,8	212,7	1131,3	818,1
Asian part of the Russian Federation																
Coniferous	416225,2	3151,4	9254,2	2178,4	8796,6	38542,0	11955,2	13071,8	73208,7	30252,2	11522,9	77515,7	48320,3	4740,8	39297,5	44417,5
Hard deciduous	12363,0	14,2	80,7	29,7	107,1	820,0	457,4	210,7	1867,5	976,3	667,6	3176,0	1436,5	272,0	1458,0	789,3
Soft deciduous	75607,3	3030,1	8451,8	1987,9	5842,8	16836,6	4319,9	4194,1	13473,4	3372,8	1963,9	6252,6	1621,3	756,2	2615,0	888,9
Forest regions of the Russian Federation																
Coniferous	73291,0	2448,8	3843,9	226,9	2893,9	6919,2	557,0	3034,4	12648,7	1275,0	1559,2	19828,8	3523,5	428,1	9222,9	4880,7
Hard deciduous	476,5	3,4	14,5	1,0	14,2	107,6	15,1	13,2	216,3	28,5	1,5	45,2	9,2	0,0	4,6	2,2
Soft deciduous	30708,0	7084,0	5322,5	258,4	3784,6	4928,0	346,3	1734,5	2834,7	262,9	528,4	1236,8	280,7	207,5	1088,9	809,8
Non-chernozem zone of the Russian Federation																
Coniferous	84079,0	4864,6	8502,2	445,3	3412,3	8222,5	611,6	3205,8	13338,0	1307,1	1616,1	20222,5	3569,1	452,2	9382,0	4927,7
Hard deciduous	615,2	81,5	311,5	23,6	22,9	146,2	14,3	2,1	11,8	0,7	0,0	0,6	0,0	0,0	0,0	0,0
Soft deciduous	39133,9	10389,0	10408,1	395,0	3897,7	4892,5	290,6	1755,1	2654,6	239,5	542,2	1273,0	282,6	208,2	1094,8	811,0
Baikal lake basin																
Coniferous	11231,0	15,5	54,6	10,5	258,7	1274,8	263,3	686,2	4492,9	1111,0	205,6	1669,3	611,7	43,4	359,3	174,2
Soft deciduous	2083,5	12,9	21,0	2,1	180,0	447,7	66,9	239,3	697,8	111,2	55,0	162,6	35,3	7,9	32,8	11,0
Shoreline around Baikal lake																
Coniferous	1683,6	5,2	13,5	2,7	65,6	218,4	41,0	122,2	483,4	112,3	54,2	248,9	97,0	20,8	128,2	70,2
Soft deciduous	411,9	6,3	8,1	0,7	49,0	80,8	9,3	49,2	86,6	16,2	19,0	40,2	11,5	5,1	20,9	9,0

Source:
http://www.iiasa.ac.at/Research/FOR/forest_cdrom/english/for_fund_en.html
(From Roslesinforg, 2003, VNIILM, 2003)

Calculation of the long run sustainable production level

Siteindexkalkyl 090323

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Sum	644972,4	24700,8	41924,5	5398,4	23338,8	73288,4	18015,9	22809,3	106253,1	36363,4	16388,1	108895,7	55312,6	6456,8	53973,6	51853,0
Sitesum				72023,7			114643,1			165425,8			180596,4			112283,4
Prod				9,0			6,0			4,5			3,4			2,0
Total Prod	2919082,6			648213,3			687858,6			744416,1			614027,8			224566,8
European-Ural part of the Russian Federation																
Coniferous	88090,6	6042,9	10183,0	543,3	3608,9	8719,6	674,5	3256,1	13493,9	1334,1	1625,1	20262,2	3576,5	452,8	9388,7	4929,0
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Sum	140776,9	18505,1	24137,8	1202,4	8592,3	17089,8	1283,4	5332,7	17703,5	1762,1	2233,7	21951,4	3934,5	687,8	10603,1	5757,3
Sitesum				43845,3			26965,5			24798,3			28119,6			17048,2
Prod				9,0			6,0			4,5			3,4			2,0
Total Prod	797696,1			394607,7			161793,0			111592,4			95606,6			34096,4
Asian part of the Russian Federation																
Coniferous	416225,2	3151,4	9254,2	2178,4	8796,6	38542,0	11955,2	13071,8	73208,7	30252,2	11522,9	77515,7	48320,3	4740,8	39297,5	44417,5
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Sum	504195,5	6195,7	17786,7	4196,0	14746,5	56198,6	16732,5	17476,6	88549,6	34601,3	14154,4	86944,3	51378,1	5769,0	43370,5	46095,7
Sitesum				28178,4			87677,6			140627,5			152476,8			95235,2
Prod				9,0			6,0			4,5			3,4			2,0
Total Prod	2121386,5			253605,6			526065,6			632823,8			518421,1			190470,4

Index (Jonson)		I	II	III	IV	V	VI	VII	VIII
m3sk/ha,year		10.5	8.0	6.0	4.5	3.4	2.5	1.8	1.2

Source:

http://www.skatteverket.se/rattsinformation/allmannarad/aldrear/1997/1997/rsvs199712a.4.18e1b10334ebe8bc80005139.html

Rough example and approximation:

All of the sustainable forest production potential in Russian Federation (2900 million cubic metres, over bark, per year) is transformed to energy.
(In reality, some fraction will probably be used for other purposes.)

With 2 TWh/Mm3, we get:

5 800 TWh/year.

China is the world's largest power generator, surpassing the United States in 2011.

Net power generation was an estimated **4,476 TWh** in 2011.

U.S. Energy Information Administration

‹ Countries

China

Last Updated: February 4, 2014 (Notes)

full report

Modern research, based on typical conditions in the north, has shown that:

The economic value (present value) of forestry, starting with forests where trees of different sizes and ages grow together, is usually higher if we use optimal continuous cover forestry than if we instantly harvest all trees and periodically start new forest generations with plantations.

Furthermore,

The forest biomass production (and net CO2 uptake) can be higher if we never harvest all trees, but always keep growing trees on the land.

Many kinds of environmental values are higher if we use continuous cover forestry than if we periodically harvest all trees.

Why focus on mixed species forests?

The presently existing forests are to a large extent mixed species forests.

Mixed species forests give more options to sequentially adapt the forests to unexpected events such as market changes, changing environmental conditions, forest fires, parasites, etc.. In several cases they can be shown to give higher expected present values than single species forests.

Mixed species forests are less sensitive to species specific parasites and diseases

Mixed species forests have environmental advantages and make it possible for more animal species to exist.

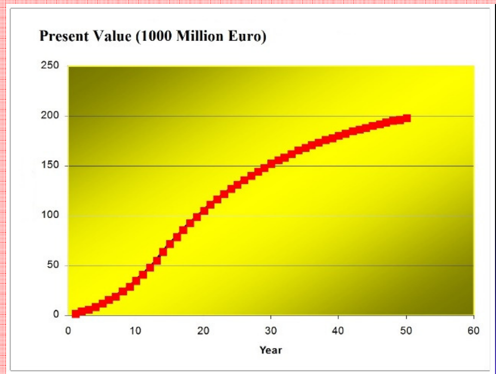
Models of biological growth should be developed that describe the

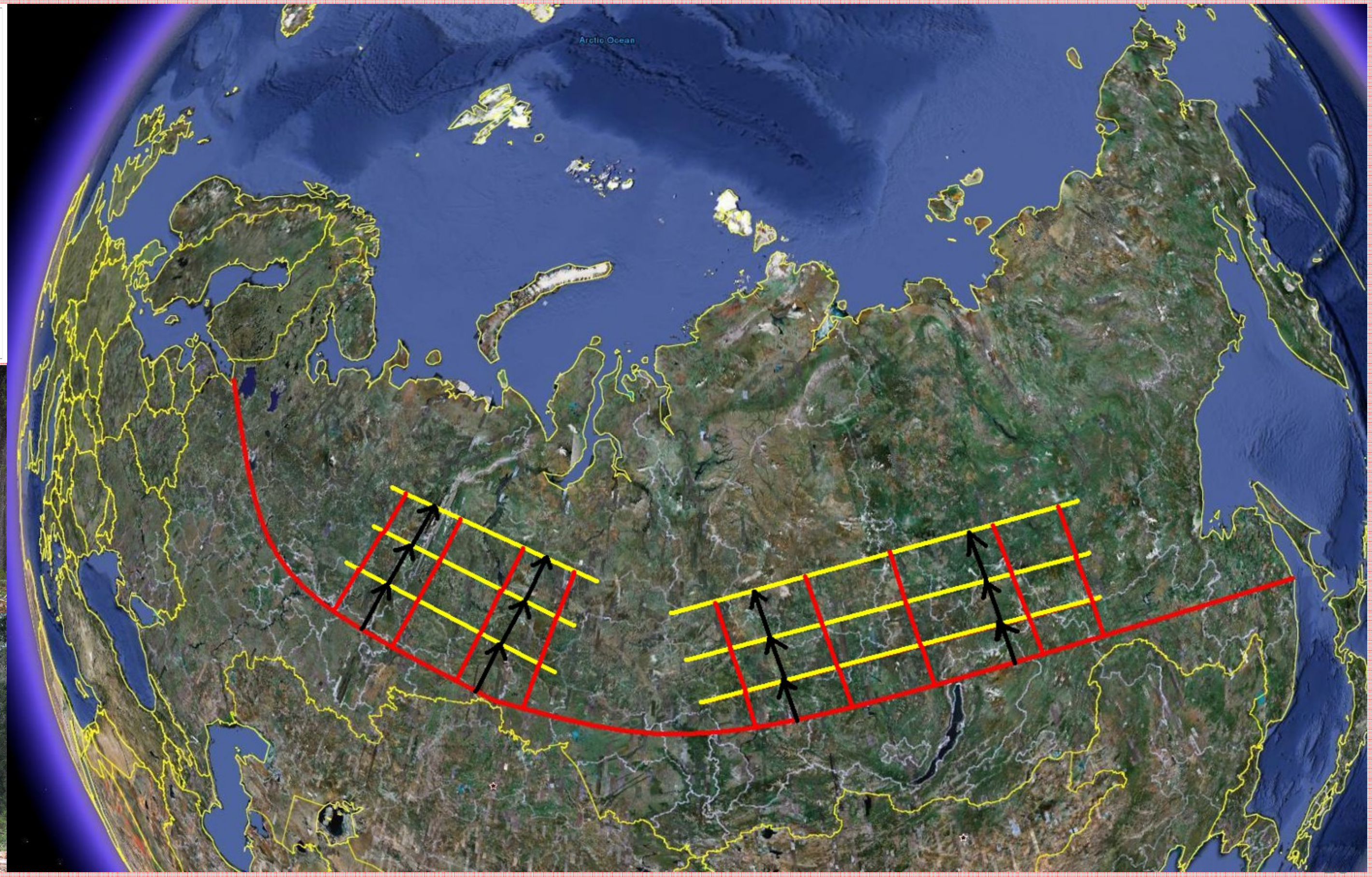
production options available over time and space.

Forest growth model development should focus on growth in forests, where trees of different sizes, ages and species, grow together.

The models should be flexible and make it possible to investigate the effects of alternative dynamic controls (harvest volumes over time) and alternative selection principles (species and dimensions).

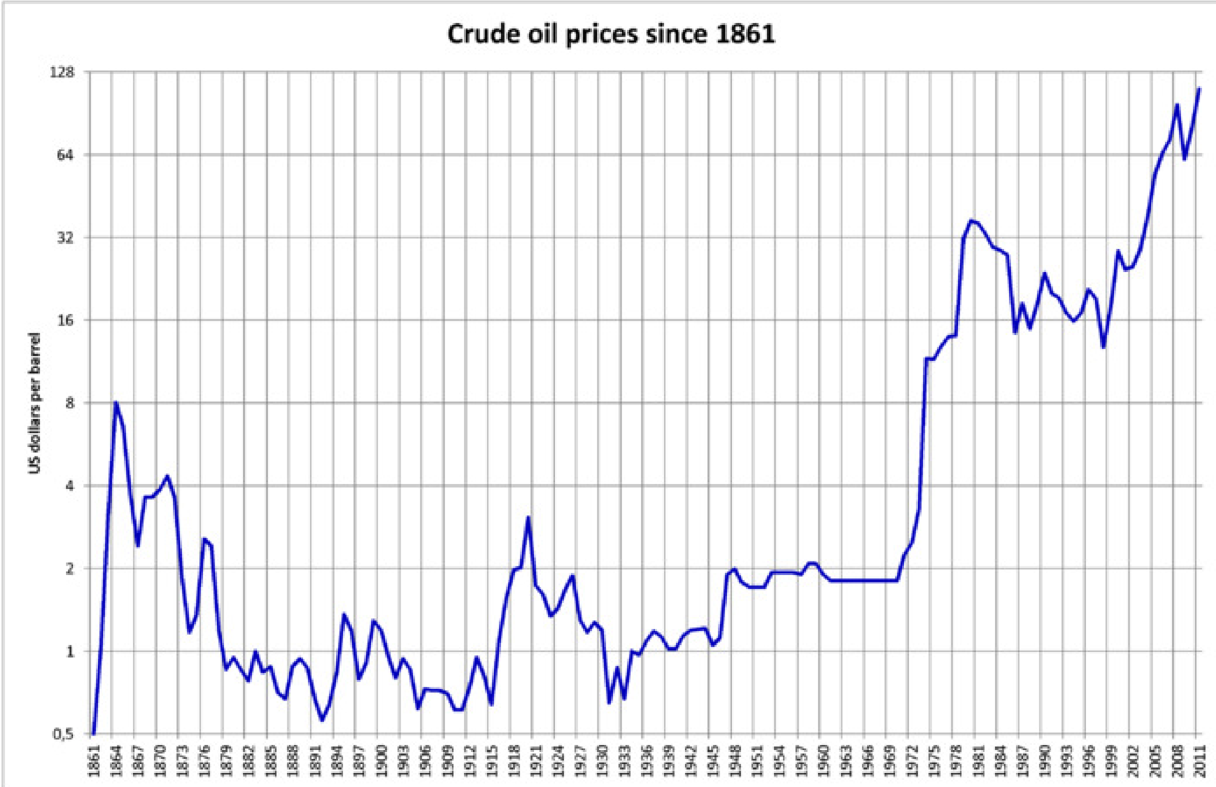
These models should have relevant scales and be possible to integrate in general optimization models with spatial and dynamic dimensions, where not only the ecological problems are in focus but all relevant economical and technical problems are included.





The latest decades clearly show that detailed deterministic long term planning is irrelevant.

Energy prices, prices of industrial products and environmental problems rapidly change in ways that cannot be perfectly predicted.



Source: http://en.wikipedia.org/wiki/Price_of_petroleum

Research in environmental ecology with consideration of a sustainable world economy should focus on the

***development of growth models that are useful when stochastic optimal control theory is applied*.**

Since biological production takes considerable time, it is very important to

create options to sequentially adjust the production

to new relative prices, growth conditions, ecological problems and possible damages caused by parasites, fire or storms.

The analysis includes

the structure of relevant stochastic optimal control problems

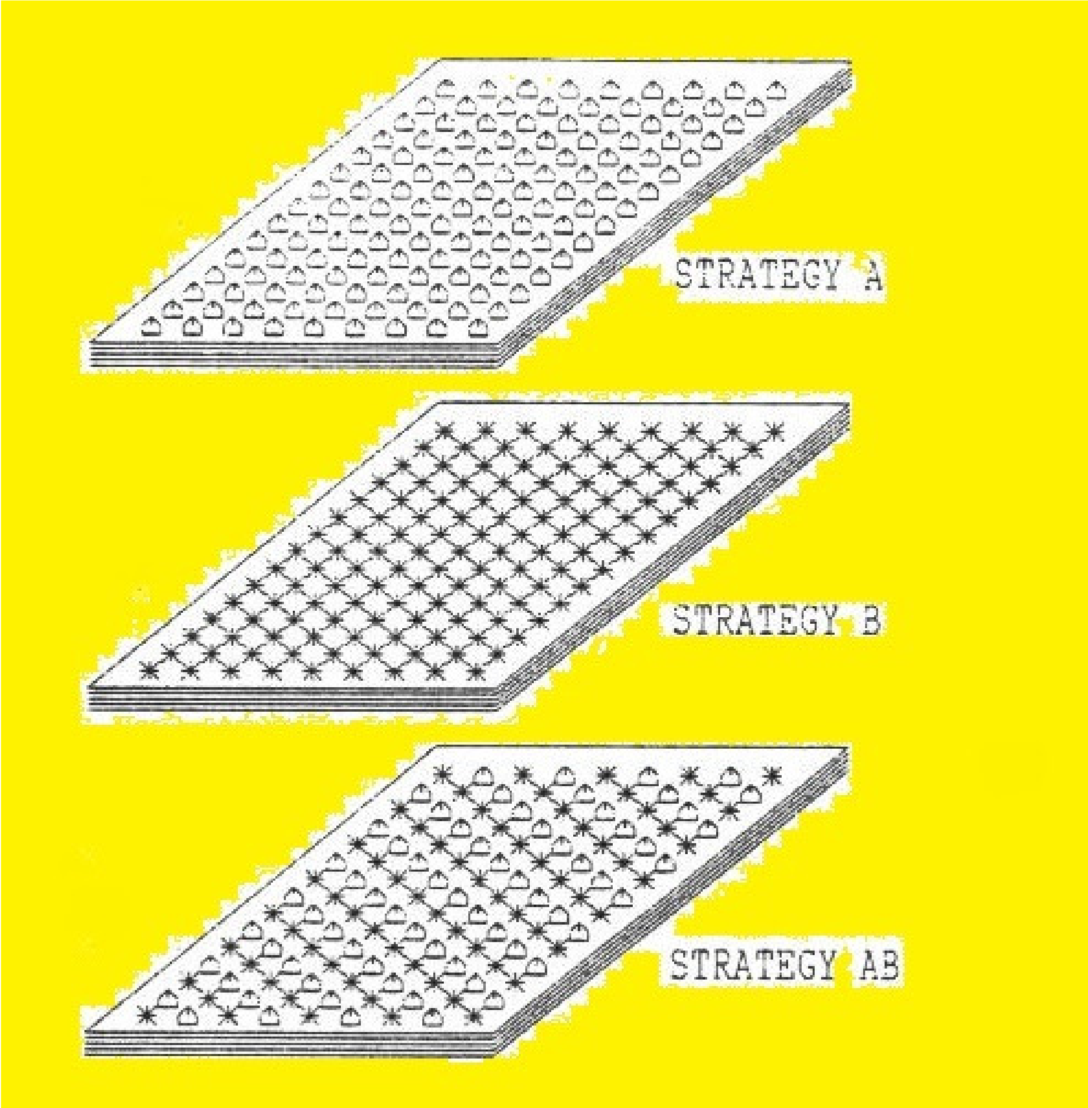
and consistent development of research in environmental ecology.

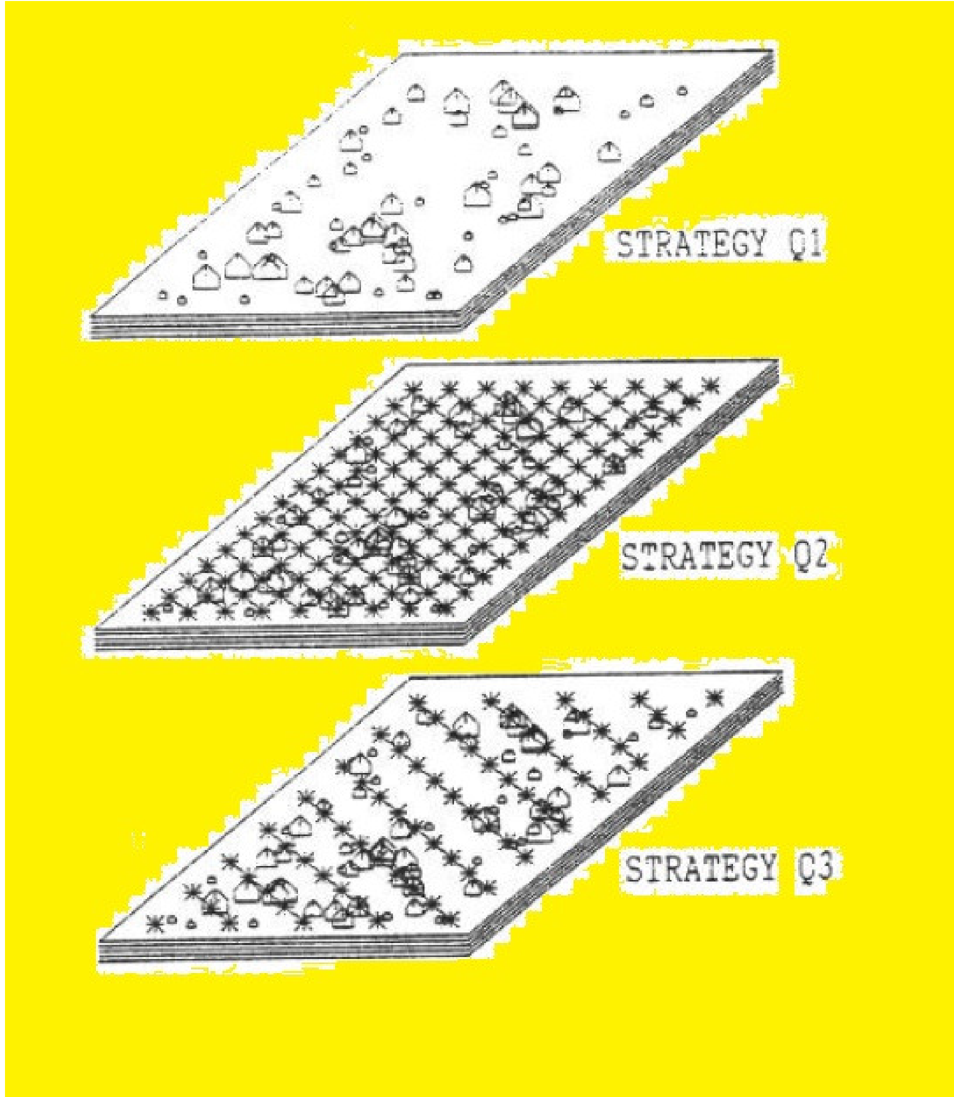
General growth functions are needed

$$\frac{dx_i}{dt} = f_i(x_1, x_2, \dots, x_n, P, t, U) \quad \forall i$$

The growth of trees (x) of different sizes and species are affected by
- the states of all trees (within some distance),
- the state of the environment, climate, etc. (P),
- time (t)
- controls (U).

Next, special cases illustrate the most central concepts and principles


STRATEGY A
STRATEGY B
STRATEGY AB


STRATEGY Q1
STRATEGY Q2
STRATEGY Q3

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Lu, F., Lohmander, P., Optimal Decisions for Mixed Forests under Risk,
Scientia Silvae Sinicae, Vol. 45, No. 11, Nov. 2009
http://www.Lohmander.com/Lu_Lohmander_2009.pdf

Will the moose eat the pine trees?

This is not known when the plantation is created.

If the forest contains several tree species, the forest production can continue even if the moose will eat the pine trees.

Optimal Management Decisions for Mixed Forests under Risk

Lu Fadian[1] Peter Lohmander[2]

(1. *College of Forestry*, *Shandong Agricultural University* *Tai' an* 271018;

2. *Dept. of Forest Economics*, *Swedish University of Agricultural Sciences* *Umea* 90183)

Abstract: Different tree species have different sensitivities to damages from different kinds of fungi, insects, and vertebrates. Prices of forest products from different tree species also change over time. Mixed forests provide valuable options for sequential adaptive management. An adaptive optimization model under the risk of moose damage and prices variation has been developed to determine the initial proportion of Norway Spruce and Scots Pine in a mixed-species stand that would maximize the expected net present value. The results showed that the mixed stand was superior to the pure pine stand even no risk was considered, due to the biological mixture effect. However, when the risk of moose damage was considered, the superiority of the mixed stand was increased by 5% and 24% with or without incorporating the minimum stem number requirement of the Forest Act, respectively. The superiority of the mixed stand over a pure pine stand could be further increased by 6% when the price risk and selective thinning were included, compared to that the price was fixed

Key words: forest management decisions; uncertainty; risk, adaptive optimization

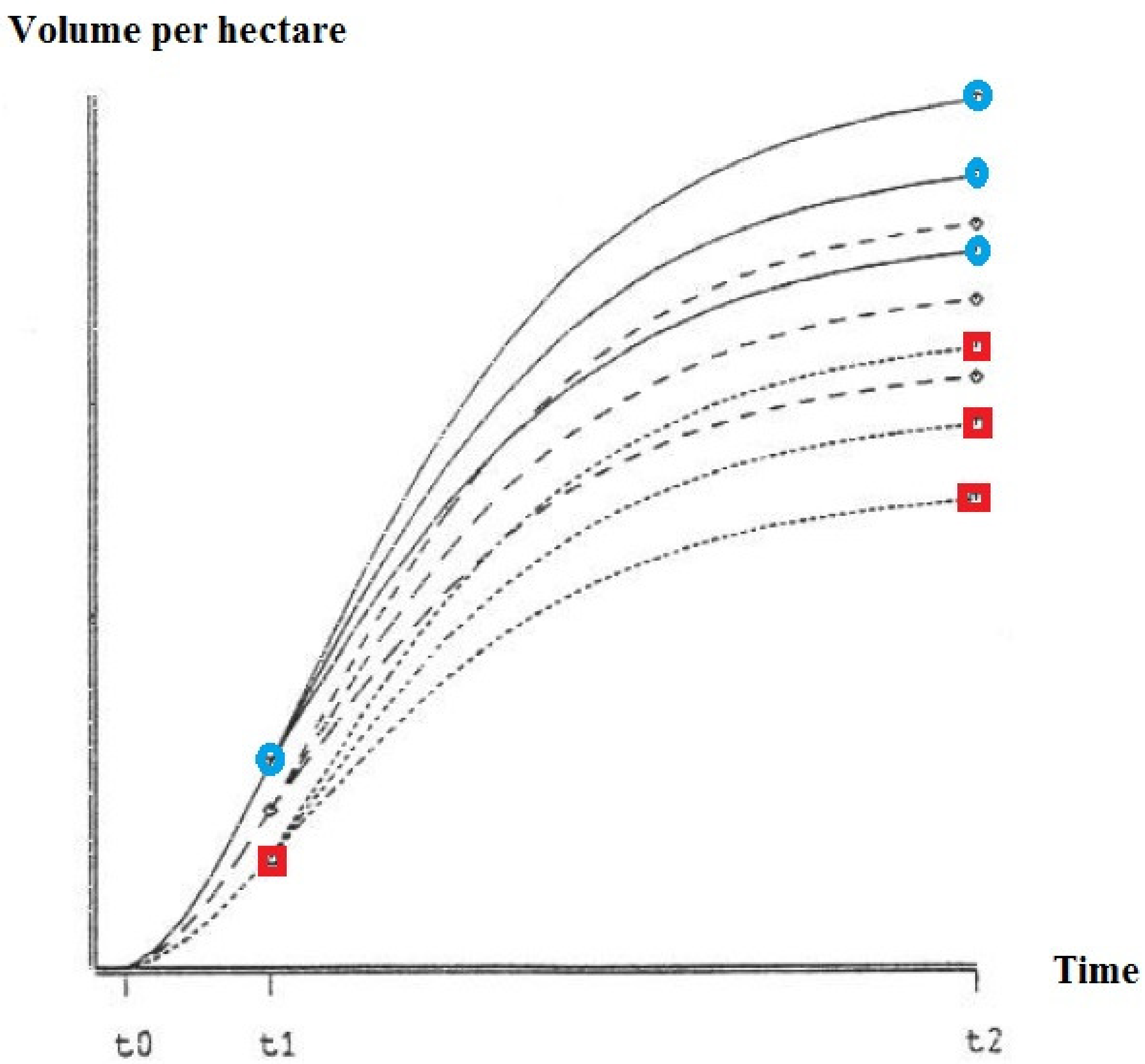
Lu, F., Lohmander, P., Optimal Decisions for Mixed Forests under Risk,
Scientia Silvae Sinicae, Vol. 45, No. 11, Nov. 2009
http://www.Lohmander.com/Lu_Lohmander_2009.pdf

How will the climate and the acidity of soils change during the next 30 years?

How will this affect the growth of different species?

That is not yet known.

If we have several species in the forest, we can change the species mix when we know more, at a later point in time.

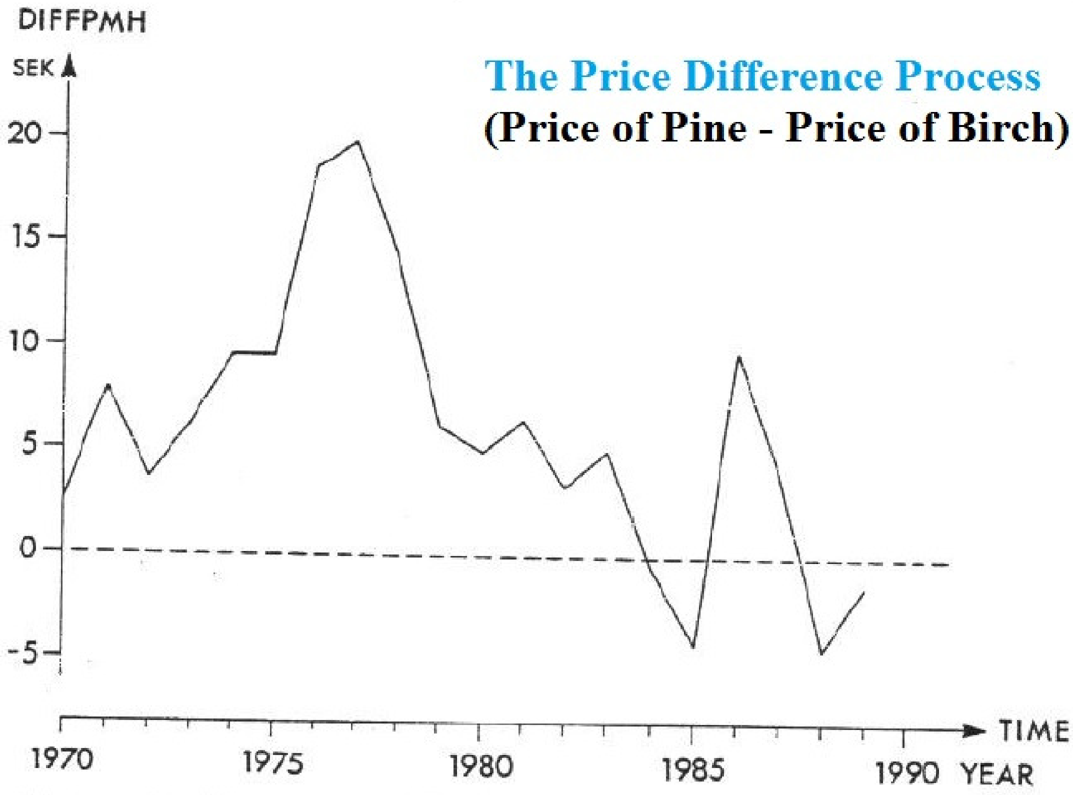


Which species will be the most valuable to industry?

That is not yet known.

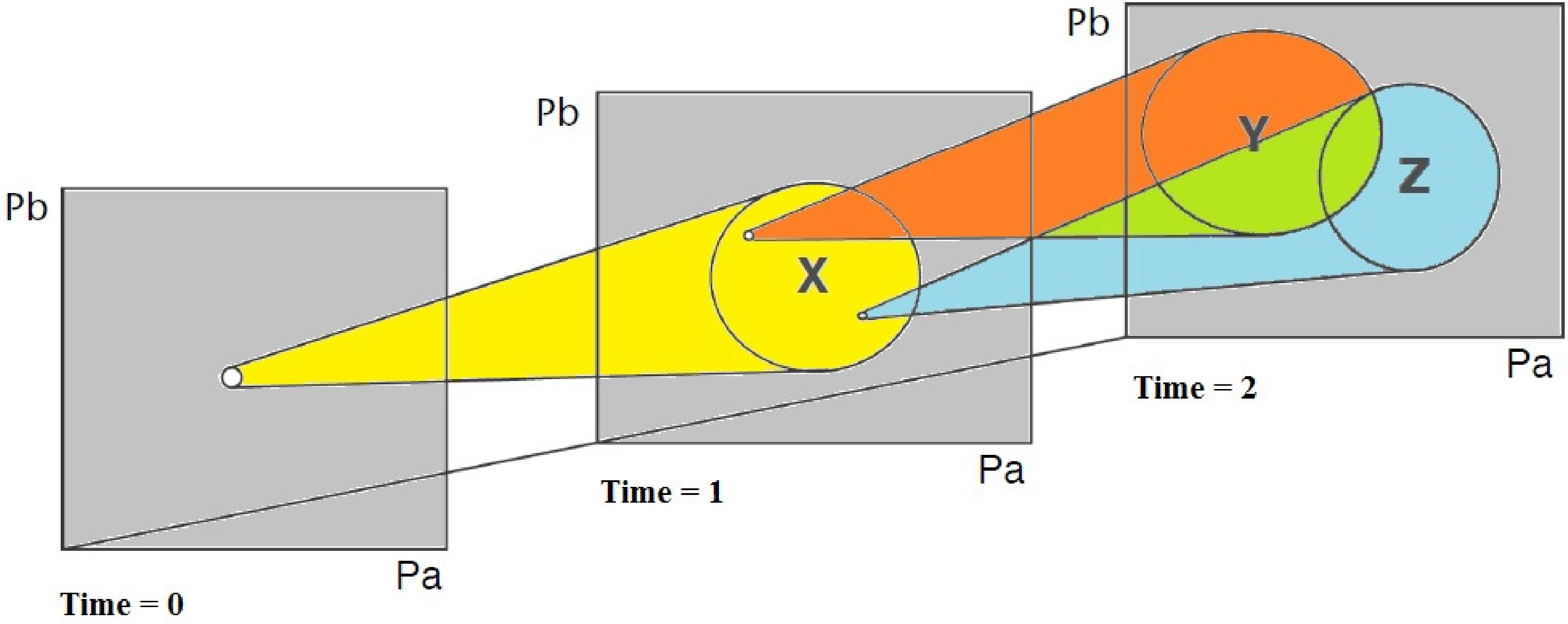
Relative prices change as a function of technical development in the process industries.

If we start with a mixed forest, we can rapidly adapt forest production and harvesting to changing prices.



With a mixed species plantation at Time 0, we can select species for continued production at Time 1.

At Time 1, we know more (than what we knew at Time 0)
and we can make a better prediction of the conditions at Time 2.

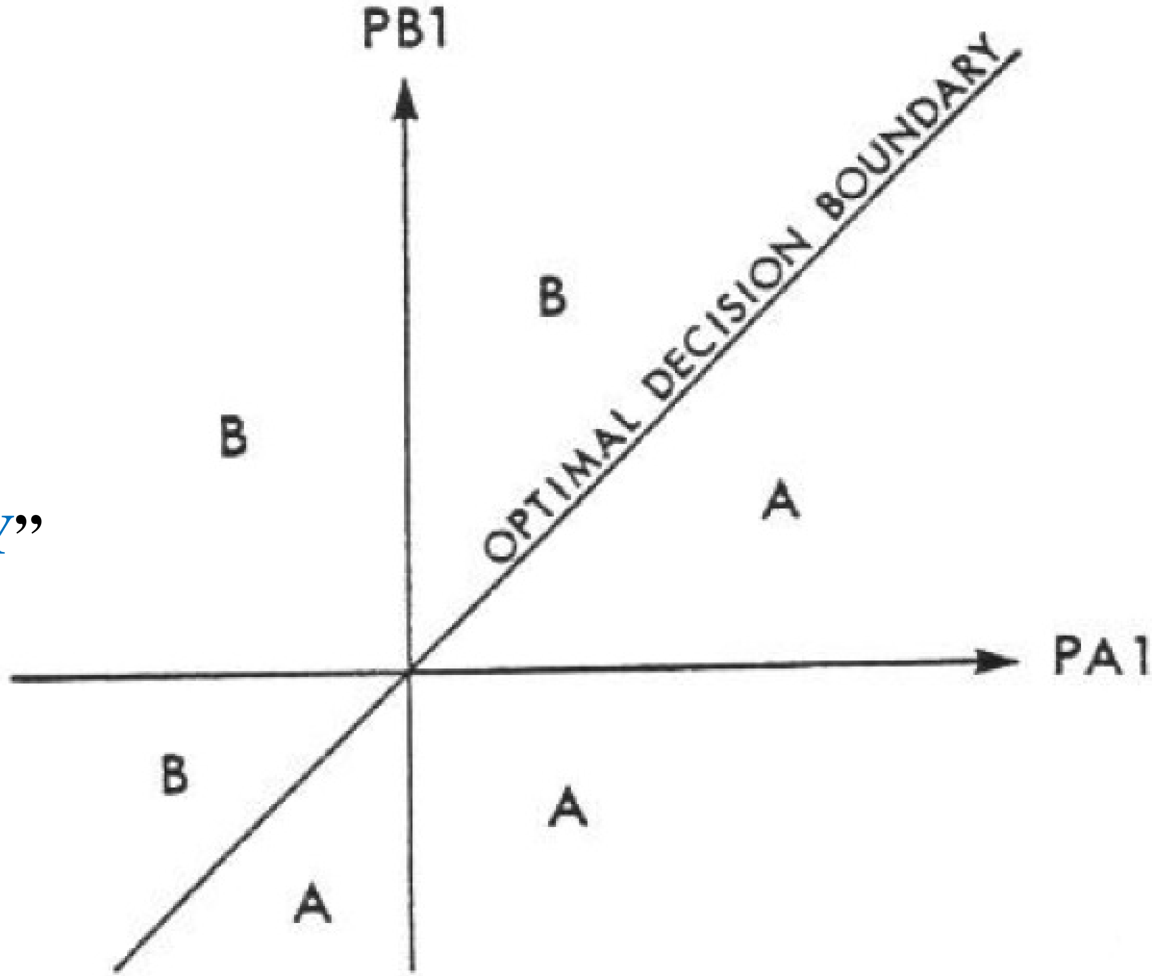


PA1 and PB1 are the prices
of species A and B at Time 1.

These prices are not known
at Time 0.

The
"OPTIMAL DECISION BOUNDARY"
is one example of a
stochastic optimal control rule.

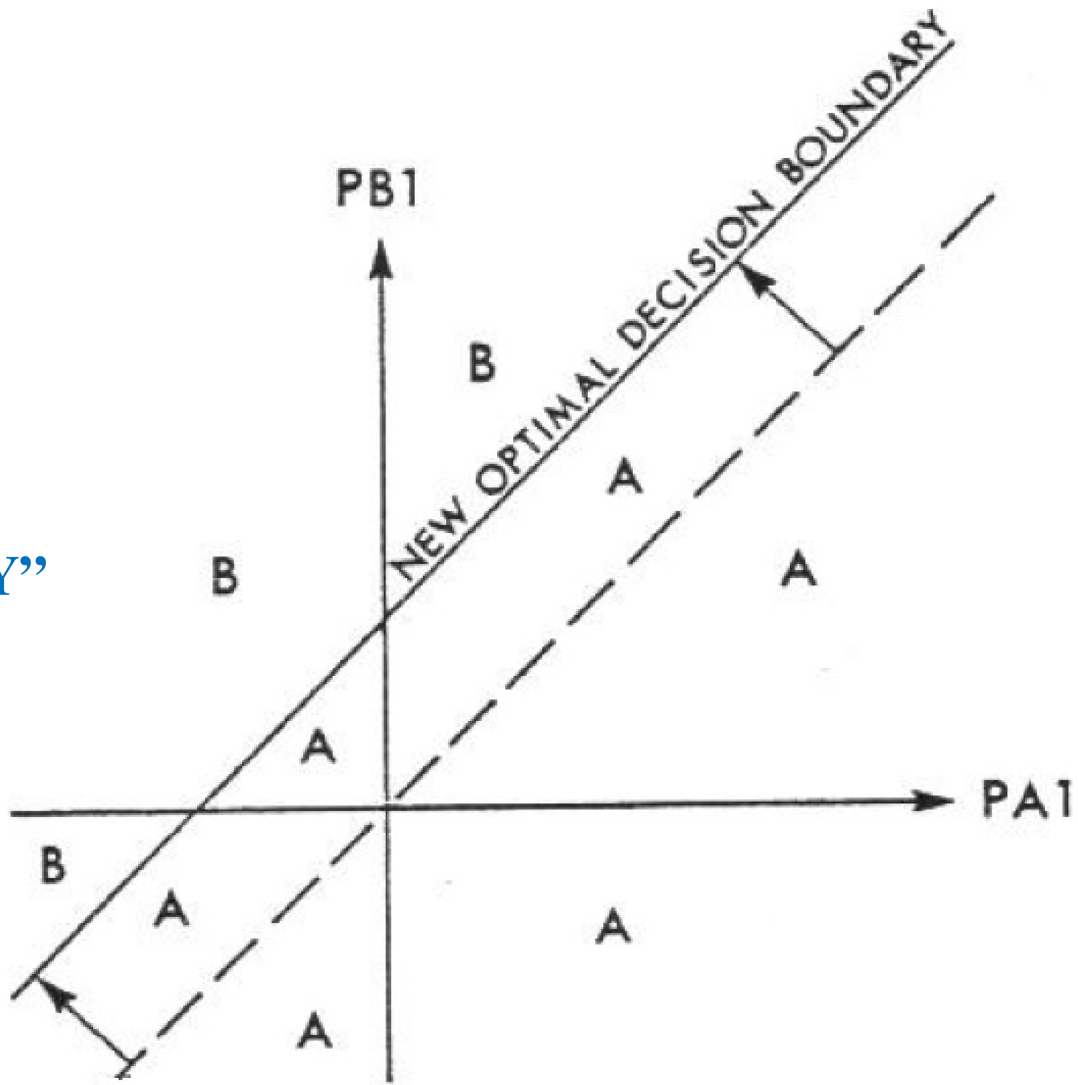
At Time 1, you should continue
production of the
species A or B depending on
the state (PA1, PB1).



With other parameters,
growth conditions,
damage probabilities
etc.,

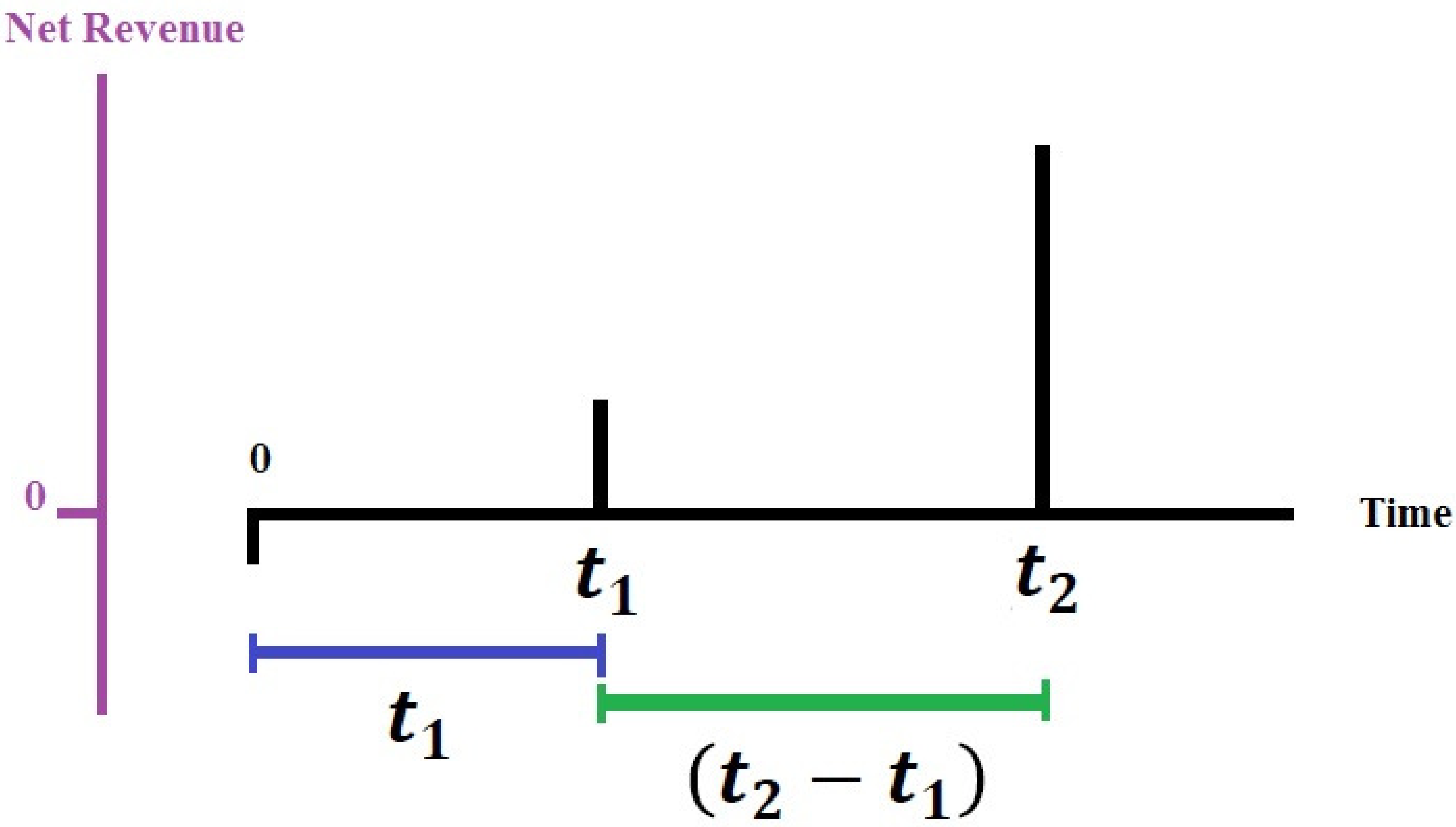
the
OPTIMAL DECISION BOUNDARY”
changes.

The graph shows what happens
if the expected growth of species A
increases in relation to the
expected growh of species B.



The stochastic prices and mixed species problem

An explorative investigation of the fundamental problem


Net Revenue
0
0
Time
t_1
t_2
t_1
$(t_2 - t_1)$

Initial price process assumptions:

Prices are real Martingale processes.

$\boldsymbol{\sigma_{AB} = 0}$.

$$P_{A_1} = P_{A_0} + \Delta P_{A_1}$$

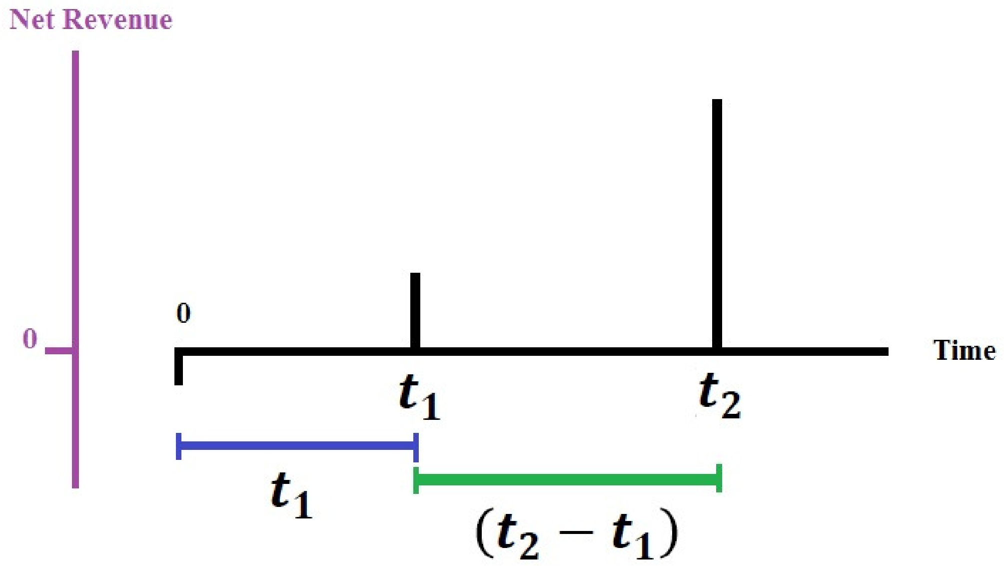
$$\Delta P_{A_1} \in N\left(0, t_1\sigma_A^2\right)$$

$$E\left(P_{A_1} \middle| P_{A_0}\right) = P_{A_0}$$

$$\Delta P_{A_1} = \Delta_1 + \Delta_2 + \cdots + \Delta_{t_1 - 1} + \Delta_{t_1}$$

$$\Delta_i \in N\left(0, \sigma_A^2\right) \ \forall i$$

$$\Delta P_{A_1} \in N\left(0, t_1 \sigma_A^2\right)$$



$$P_{A_2} = P_{A_1} + \Delta P_{A_2}$$

$$\Delta P_{A_2} \in N\left(0, (t_2 - t_1)\sigma_A^2\right)$$

$$E\left(P_{A_2} \middle| P_{A_1}\right) = P_{A_1}$$

$$E\left(P_{A_2} \middle| P_{A_0}\right) = P_{A_0}$$

In most cases, $P_{A_1} \neq P_{A_0}$

Observation:

$$E(P_{A_2}|P_{A_1}) - E(P_{A_2}|P_{A_0}) \begin{cases} > 0 \text{ } if \text{ } (P_{A_1} > P_{A_0}) \\ = 0 \text{ } if \text{ } (P_{A_1} = P_{A_0}) \\ < 0 \text{ } if \text{ } (P_{A_1} < P_{A_0}) \end{cases}$$

$$P_{B_1} = P_{B_0} + \Delta P_{B_1}$$
$$\Delta P_{B_1} \in N\left(0, t_1 \sigma_B^2\right)$$
$$E(P_{B_1} | P_{B_0}) = P_{B_0}$$

$$P_{B_2} = P_{B_1} + \Delta P_{B_2}$$
$$\Delta P_{B_2} \in N\left(0, (t_2 - t_1)\sigma_B^2\right)$$
$$E(P_{B_2} | P_{B_1}) = P_{B_1}$$
$$E(P_{B_2} | P_{B_0}) = P_{B_0}$$

In most cases, $P_{B_1} \neq P_{B_0}$

Observation:

$$E(P_{B_2}|P_{B_1}) - E(P_{B_2}|P_{B_0}) \begin{cases} > 0 \; if \; (P_{B_1} > P_{B_0}) \\ = 0 \; if \; (P_{B_1} = P_{B_0}) \\ < 0 \; if \; (P_{B_1} < P_{B_0}) \end{cases}$$

$$d_1 = e^{-rt_1}, d_2 = e^{-rt_2}$$

Expected present value of management system A without adaptive decisions:

$$\pi_A = E\left(\left(-c_A + d_1 P_{A_1} h_{A_1} + d_2 P_{A_2} h_{A_2}\right) \middle| P_{A_0}\right)$$

$$\pi_A = -c_A + d_1 E(P_{A_1} | P_{A_0}) h_{A_1} + d_2 E(P_{A_2} | P_{A_0}) h_{A_2}$$

$$E(P_{A_1} \mid P_{A_0}) = P_{A_0}$$
$$E(P_{A_2} \mid P_{A_1}) = P_{A_1}$$

$$\pi_A = -c_A + d_1 P_{A_0} h_{A_1} + d_2 P_{A_0} h_{A_2}$$

Expected present value of management system B without adaptive decisions:

$$\pi_B = E\left(\left(-c_B + d_1 P_{B_1} h_{B_1} + d_2 P_{B_2} h_{B_2}\right) \middle| P_{B_0}\right)$$

$$\pi_B = -c_B + d_1 E\left(P_{B_1} \middle| P_{B_0}\right) h_{B_1} + d_2 E\left(P_{B_2} \middle| P_{B_0}\right) h_{B_2}$$

$$E\left(P_{B_1} \middle| P_{B_0}\right) = P_{B_0}$$

$$E\left(P_{B_2} \middle| P_{B_1}\right) = P_{B_1}$$

$$\pi_B = -c_B + d_1 P_{B_0} h_{B_1} + d_2 P_{B_0} h_{B_2}$$

Expected present value of a management system AB with adaptive decisions. (50% of the stems are removed at t_1.)

$$\pi_{AB} = \begin{pmatrix} -\dfrac{(c_A + c_B)}{2} - k \\ + \\ \phi\left(\left(d_1 P_{B_1} h_{B_1} + d_2 E(P_{A_2} \middle| P_{A_1}) h_{A_2} \geq d_1 P_{A_1} h_{A_1} + d_2 E(P_{B_2} | P_{B_1}) h_{B_2}) \middle| (P_{A_0}, P_{B_0}\right)\right) Z_1 \\ + \\ \phi\left(\left(d_1 P_{B_1} h_{B_1} + d_2 E(P_{A_2} \middle| P_{A_1}) h_{A_2} < d_1 P_{A_1} h_{A_1} + d_2 E(P_{B_2} | P_{B_1}) h_{B_2}) \middle| (P_{A_0}, P_{B_0}\right)\right) Z_2 \end{pmatrix}$$

$$\boldsymbol{Z_1 = E\left(d_1 P_{B_1} h_{B_1} + d_2 P_{A_2} h_{A_2} \middle| \left(P_{A_0}, P_{B_0}, \left(d_1 P_{B_1} h_{B_1} + d_2 E(P_{A_2} \middle| P_{A_1}) h_{A_2} \geq d_1 P_{A_1} h_{A_1} + d_2 E(P_{B_2} \middle| P_{B_1}) h_{B_2}\right)\right)\right)}$$

$$\boldsymbol{Z_2 = E\left(d_1 P_{A_1} h_{A_1} + d_2 P_{B_2} h_{B_2} \middle| \left(P_{A_0}, P_{B_0}, \left(d_1 P_{B_1} h_{B_1} + d_2 E(P_{A_2} \middle| P_{A_1}) h_{A_2} < d_1 P_{A_1} h_{A_1} + d_2 E(P_{B_2} \middle| P_{B_1}) h_{B_2}\right)\right)\right)}$$

$$\pi_{AB} = -\frac{(c_A + c_B)}{2} - k + \phi Z_1 + (1 - \phi) Z_2$$

$$\pi_{AB} = -\frac{(c_A + c_B)}{2} - k + \phi Z_1 + (1 - \phi) Z_2$$

$$\phi = \phi\left(\left(d_1\, P_{B_1} h_{B_1} + d_2\, E(P_{A_2} \middle| P_{A_1}) h_{A_2} \geq d_1 P_{A_1} h_{A_1} + d_2\, E(P_{B_2} \middle| P_{B_1}) h_{B_2}\right) \middle| (P_{A_0}, P_{B_0})\right)$$

$$Z_1 = E\left(d_1 P_{B_1} h_{B_1} + d_2 P_{A_2} h_{A_2} \middle| \left(P_{A_0}, P_{B_0}, (d_1 P_{B_1} h_{B_1} + d_2 E(P_{A_2} | P_{A_1}) h_{A_2} \geq d_1 P_{A_1} h_{A_1} + d_2 E(P_{B_2} | P_{B_1}) h_{B_2})\right)\right)$$

$$Z_2 = E\left(d_1 P_{A_1} h_{A_1} + d_2 P_{B_2} h_{B_2} \middle| \left(P_{A_0}, P_{B_0}, (d_1 P_{B_1} h_{B_1} + d_2 E(P_{A_2} | P_{A_1}) h_{A_2} < d_1 P_{A_1} h_{A_1} + d_2 E(P_{B_2} | P_{B_1}) h_{B_2})\right)\right)$$

Case 1:

Harvest revenues at t_1 are not affected by the timber prices P_{A_1} and P_{B_1} (since harvests at t_1 do not give timber but other assortments, such as energy assortments and pulp wood.)

We assume that all management alternatives lead to the same net present values of harvests at t_1.

In order to make the following derivations easier to follow, we exclude the present values of harvests at t_1 from π_A, π_B and π_{AB}.

We also assume that the timber harvest volumes are the same, h, for both species.

$$\pi_A = -c_A + d_2 E(P_{A_2} \mid P_{A_0}) h_{A_2}$$

$$\pi_A = -c_A + d_2 P_{A_0} h$$

$$\pi_B = -c_B + d_2 E(P_{B_2} \mid P_{B_0}) h_{B_2}$$

$$\pi_B = -c_B + d_2 P_{B_0} h$$

$$\pi_{AB} = -\frac{(c_A + c_B)}{2} - k + \phi Z_1 + (1-\phi) Z_2$$

$$\phi = \phi\left(\left(d_2 E(P_{A_2} | P_{A_1}) h_{A_2} \geq d_2 E(P_{B_2} | P_{B_1}) h_{B_2}\right) \Big| (P_{A_0}, P_{B_0})\right)$$

$$\phi = \phi\left(\left(d_2 P_{A_1} h_{A_2} \geq d_2 P_{B_1} h_{B_2}\right) \Big| (P_{A_0}, P_{B_0})\right)$$

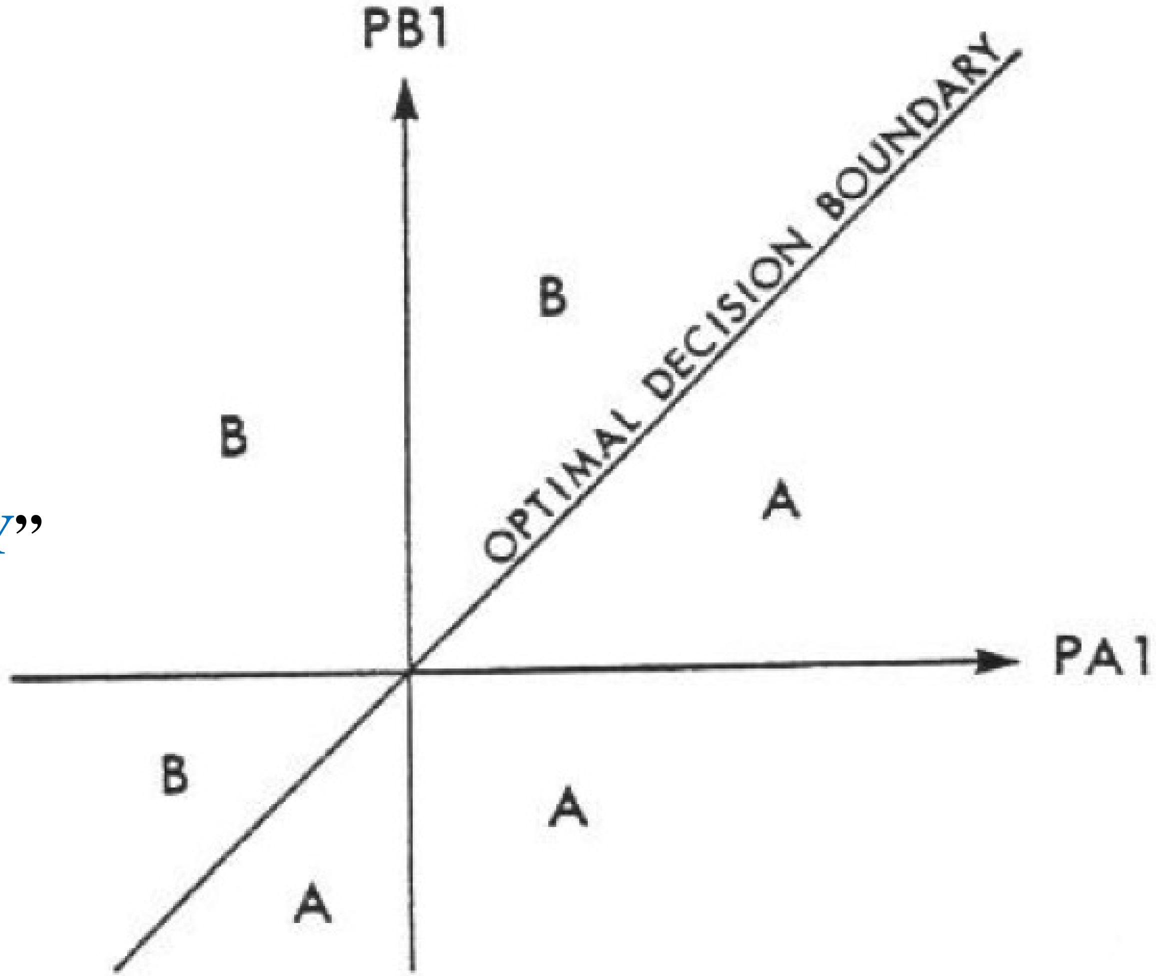
$$\phi = \phi\left(\left(P_{A_1} \geq P_{B_1}\right) \Big| (P_{A_0}, P_{B_0})\right)$$

PA1 and PB1 are the prices of species A and B at Time 1.

These prices are not known at Time 0.

The "OPTIMAL DECISION BOUNDARY" is one example of a stochastic optimal control rule.

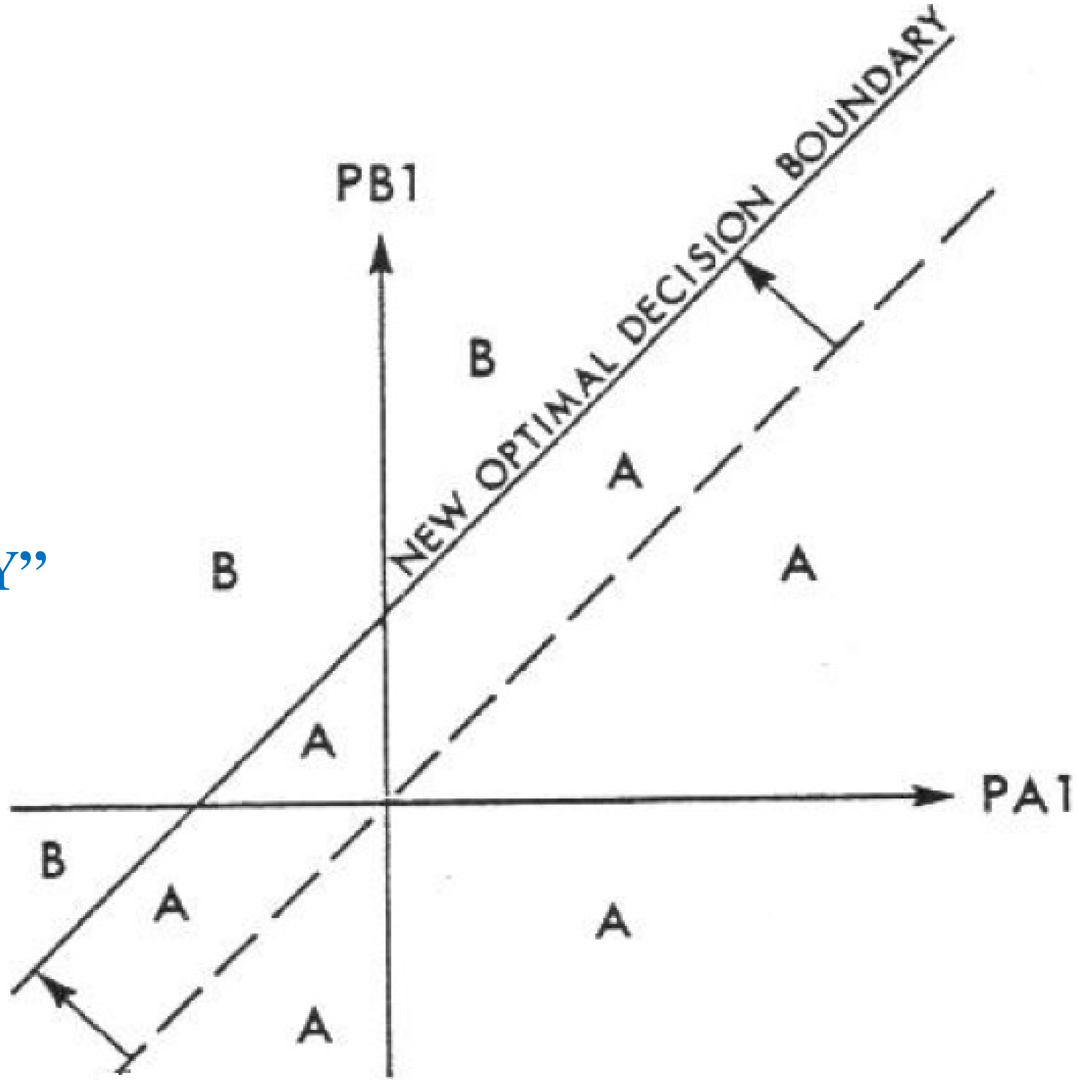
At Time 1, you should continue production of the species A or B depending on the state (PA1, PB1).



With other parameters,
growth conditions,
damage probabilities
etc.,

the
OPTIMAL DECISION BOUNDARY"
changes.

The graph shows what happens if the expected growth of species A increases in relation to the expected growh of species B.



$$Z_1 = E\left(d_2 P_{A_2} h_{A_2} \middle| \left(P_{A_0}, P_{B_0}, \left(E(P_{A_2}|P_{A_1}) h_{A_2} \geq E(P_{B_2}|P_{B_1}) h_{B_2}\right)\right)\right)$$

$$Z_1 = d_2 E\left(P_{A_2} \middle| \left(P_{A_0}, P_{B_0}, \left(P_{A_1} \geq P_{B_1}\right)\right)\right) h$$

$$Z_2 = E\left(d_2 P_{B_2} h_{B_2} \middle| \left(P_{A_0}, P_{B_0}, \left(E(P_{A_2} | P_{A_1}) h_{A_2} < E(P_{B_2} | P_{B_1}) h_{B_2}\right)\right)\right)$$

$$Z_2 = d_2 E\left(P_{B_2} \middle| \left(P_{A_0}, P_{B_0}, \left(P_{A_1} < P_{B_1}\right)\right)\right) h$$

Summary of Case 1:

$$\boldsymbol{\pi_A = -c_A + d_2 P_{A_0} h}$$

$$\boldsymbol{\pi_B = -c_B + d_2 P_{B_0} h}$$

$$\boldsymbol{\pi_{AB} = -\frac{(c_A + c_B)}{2} - k + \phi Z_1 + (1 - \phi) Z_2}$$

$$\pi_{AB} = -\frac{(c_A + c_B)}{2} - k + \phi Z_1 + (1-\phi) Z_2$$

$$\phi = \phi\left(\left(P_{A_1} \geq P_{B_1}\right) \middle| \left(P_{A_0}, P_{B_0}\right)\right)$$

$$Z_1 = d_2 E\left(P_{A_2} \middle| \left(P_{A_0}, P_{B_0}, \left(P_{A_1} \geq P_{B_1}\right)\right)\right) h$$

$$Z_2 = d_2 E\left(P_{B_2} \middle| \left(P_{A_0}, P_{B_0}, \left(P_{A_1} < P_{B_1}\right)\right)\right) h$$

Case 2:

As Case 1 with the following constraints:

$$\boldsymbol{\sigma_B = 0}$$

$$\boldsymbol{(\sigma_B = 0) \Longrightarrow \left(\Delta P_{B_1} = 0\,;\ \Delta P_{B_2} = 0\right)}$$

$$\boldsymbol{P_{A_0} = P_{B_0}}$$

$$p = P_{A_1} - P_{B_1}$$

$$f(p) = \begin{cases} 0 , & p \le -g \\ g^{-1} + g^{-2}p , & -g < p < 0 \\ g^{-1} , & p = 0 \\ g^{-1} - g^{-2}p , & 0 < p < g \\ 0 , & p \ge g \end{cases}$$

$$\boldsymbol{\pi_{AB} = -\frac{(c_A + c_B)}{2} - k + \phi Z_1 + (1 - \phi) Z_2}$$

$$\boldsymbol{\phi = \frac{1}{2}}$$

$$\boldsymbol{Z_1 = \left(2d_2 \int_0^g (\alpha + \beta p) f(p) dp \right) h}$$

$$Z_1 = \left(2d_2 \int_0^g (\alpha + \beta p) f(p)\, dp \right) h$$

$$Z_3 = \frac{Z_1}{2d_2 h}$$

$$Z_3 = \int_0^g (\alpha + \beta p) f(p)\, dp$$

$$\boldsymbol{Z_3 = \int_0^g (\alpha + \beta p) f(p)\, dp}$$

$$\boldsymbol{Z_3 = \int_0^g (\alpha + \beta p)\left(g^{-1} - g^{-2} p\right) dp}$$

$$\boldsymbol{Z_3 = \int_0^g \left(\alpha g^{-1} - \alpha g^{-2} p + \beta g^{-1} p - \beta g^{-2} p^2\right) dp}$$

$$Z_3 = \int_0^g \left(\alpha g^{-1} - \alpha g^{-2}p + \beta g^{-1}p - \beta g^{-2}p^2\right)dp$$

$$Z_3 = \left[\alpha g^{-1}p - \frac{\alpha g^{-2}p^2}{2} + \frac{\beta g^{-1}p^2}{2} - \frac{\beta g^{-2}p^3}{3}\right]_0^g$$

$$Z_3 = \alpha g^{-1}g - \frac{\alpha g^{-2}g^2}{2} + \frac{\beta g^{-1}g^2}{2} - \frac{\beta g^{-2}g^3}{3}$$

$$\boldsymbol{Z_3 = \alpha g^{-1} g - \frac{\alpha g^{-2} g^2}{2} + \frac{\beta g^{-1} g^2}{2} - \frac{\beta g^{-2} g^3}{3}}$$

$$\boldsymbol{Z_3 = \alpha - \frac{\alpha}{2} + \frac{\beta g}{2} - \frac{\beta g}{3}}$$

$$\boldsymbol{Z_3 = \frac{\alpha}{2} + \left(\frac{1}{2} - \frac{1}{3}\right) \beta g}$$

$$Z_3 = \frac{\alpha}{2} + \left(\frac{1}{2} - \frac{1}{3}\right)\beta g$$

$$Z_3 = \frac{\alpha}{2} + \left(\frac{3}{6} - \frac{2}{6}\right)\beta g$$

$$Z_3 = \frac{\alpha}{2} + \frac{\beta}{6} g$$

$$Z_1 = 2 d_2 h\left(\frac{\alpha}{2} + \frac{\beta}{6} g\right)$$

$$Z_1 = d_2 h\left(\alpha + \frac{\beta}{3} g\right)$$

$$\boldsymbol{Z_2} = \boldsymbol{d_2 E\left(P_{B_2} \middle| \left(P_{A_0}, P_{B_0}, \left(P_{A_1} < P_{B_1}\right)\right)\right) h}$$

$$\boldsymbol{Z_2} = \boldsymbol{d_2 P_{B_0} h}$$

Observation: $\boldsymbol{Z_1 = d_2 h\left(\alpha + \frac{\beta}{3} g\right)}$

For g=0:

$$\boldsymbol{Z_1 = d_2 h \alpha}$$

$$\boldsymbol{Z_2 = d_2 P_{B_0} h}$$

$$\boldsymbol{d_2 h \alpha = d_2 P_{B_0} h}$$

$$\boldsymbol{\alpha = P_{B_0}}$$

Comparison of investments for g=0:

$$\pi_A = -c_A + d_2 P_{A_0} h$$

$$\pi_B = -c_B + d_2 P_{B_0} h$$

$$\pi_{AB} = -\frac{(c_A + c_B)}{2} - k + \phi Z_1 + (1 - \phi) Z_2$$

$$\pi_{AB} = -\frac{(c_A + c_B)}{2} - k + \phi Z_1 + (1 - \phi) Z_2$$

$$\pi_{AB} = -\frac{(c_A + c_B)}{2} - k + \frac{1}{2} d_2 h \left(\alpha + \frac{\beta}{3} g \right) + \frac{1}{2} d_2 P_{B_0} h$$

$$\pi_{AB} = -\frac{(c_A + c_B)}{2} - k + \frac{1}{2} d_2 h \left(\alpha + \frac{\beta}{3} 0 \right) + \frac{1}{2} d_2 P_{B_0} h$$

$$\pi_{AB} = -\frac{(c_A + c_B)}{2} - k + \frac{1}{2} d_2 h \alpha + \frac{1}{2} d_2 P_{B_0} h$$

$$\alpha = P_{B_0}$$

$$\pi_{AB} = -\frac{(c_A + c_B)}{2} - k + \frac{1}{2} d_2 h P_{B_0} + \frac{1}{2} d_2 P_{B_0} h$$

$$\pi_{AB} = -\frac{(c_A + c_B)}{2} - k + d_2 P_{B_0} h$$

$$P_{A_0} = P_{B_0} = P_0$$

Let $c_A = c_B = c$

$$\pi_A = -c_A + d_2 P_{A_0} h$$

$$\pi_A = -c + d_2 P_0 h$$

$$\pi_B = -c_B + d_2 P_{B_0} h$$

$$\pi_B = -c + d_2 P_0 h$$

$$\boldsymbol{\pi_{AB} = -\frac{(c_A + c_B)}{2} - k + d_2 P_{B_0} h}$$

$$\boldsymbol{\pi_{AB} = -c - k + d_2 P_0 h}$$

Then,

$$\boldsymbol{\pi_A = \pi_B = \pi_1}$$

Standard assumption: $\mathbf{k > 0}$.

$$(\mathbf{g = 0} \wedge \boldsymbol{k} > \mathbf{0}) \Rightarrow (\boldsymbol{\pi_{AB} < \pi_A = \pi_B})$$

Comparative statics for g > 0:

$$\pi_{AB} = -\frac{(c_A + c_B)}{2} - k + \phi Z_1 + (1 - \phi) Z_2$$

$$\pi_{AB} = -\frac{(c_A + c_B)}{2} - k + \frac{1}{2} d_2 h \left(\alpha + \frac{\beta}{3} g \right) + \frac{1}{2} d_2 P_{B_0} h$$

$$\frac{d\pi_{AB}}{dg} = \frac{d_2 h \beta}{6} > 0$$

Observation:

$$\Delta\pi = \pi_{AB} - \pi_1 = -k + \frac{d_2 h\beta}{6} g$$

$$\Delta\pi = \pi_{AB} - \pi_1 \begin{cases} < 0, & k > \dfrac{d_2 h\beta}{6} g \\ = 0, & k = \dfrac{d_2 h\beta}{6} g \\ > 0, & k < \dfrac{d_2 h\beta}{6} g \end{cases}$$

General comparative statics analysis:

$$\pi_{AB} = -\frac{(c_A + c_B)}{2} - k + \phi Z_1 + (1 - \phi) Z_2$$

$$\phi = \phi(\sigma_A, \dots)$$
$$Z_1 = Z_1(\sigma_A, \dots)$$
$$Z_2 = Z_2(\sigma_A, \dots)$$

$$\boldsymbol{\pi_{AB} = -\frac{(c_A + c_B)}{2} - k + \phi(\sigma_A) Z_1(\sigma_A) + (1 - \phi(\sigma_A)) Z_2(\sigma_A)}$$

$$\pi_{AB} = -\frac{(c_A + c_B)}{2} - k + \phi(\sigma_A) Z_1(\sigma_A) + (1 - \phi(\sigma_A)) Z_2(\sigma_A)$$

$$\frac{d\pi_{AB}}{d\sigma_A} = \frac{d\phi(\sigma_A)}{d\sigma_A} Z_1(\sigma_A) + \phi(\sigma_A) \frac{dZ_1(\sigma_A)}{d\sigma_A} - \frac{d\phi(\sigma_A)}{d\sigma_A} Z_2(\sigma_A) + (1 - \phi(\sigma_A)) \frac{dZ_2(\sigma_A)}{d\sigma_A}$$

$$\frac{d\pi_{AB}}{d\sigma_A} = \frac{d\phi(\sigma_A)}{d\sigma_A} (Z_1 - Z_2) + \phi(\sigma_A) \frac{dZ_1(\sigma_A)}{d\sigma_A} + (1 - \phi(\sigma_A)) \frac{dZ_2(\sigma_A)}{d\sigma_A}$$

Observation:

On the decision boundary, the expected present values of A and B are the same,

$$Z_1 - Z_2 = 0$$

Usually,

$$\left|\frac{dZ_2(\sigma_{A},.)}{d\sigma_A}\right| \ll \left|\frac{dZ_1(\sigma_{A},.)}{d\sigma_A}\right| \text{ and } \frac{dZ_1(\sigma_A)}{d\sigma_A} > 0$$

$\phi(\sigma_A,.)$ **and** $\left(1-\phi(\sigma_A,.)\right)$ **are strictly positive and of the same order of magnitude. Then:**

$$\frac{d\pi_{AB}}{d\sigma_A} \approx \phi(\sigma_A)\frac{dZ_1(\sigma_A)}{d\sigma_A} > 0$$

Observation:

$$\Delta\pi = \pi_{AB} - \pi_1 = -k + w(\sigma_A)$$

$$\frac{dw(\sigma_A)}{d\sigma_A} > 0$$

$$\Delta\pi = \pi_{AB} - \pi_1 \begin{cases} < 0\ , & k > w(\sigma_A) \\ = 0\ , & k = w(\sigma_A) \\ > 0\ , & k < w(\sigma_A) \end{cases}$$

CONCLUSIONS:

In typical cases:

If $\sigma_A = 0$, a one species plantation gives the highest expected present value.

At some strictly positive and unique value of σ_A , investments in one or two species give the same expected present value.

At higher values of σ_A , a two species investment gives a strictly higher expected present value than a one species investment.

Conclusions:

- The latest decades clearly show that detailed deterministic long term planning is irrelevant.
- Energy prices, prices of industrial products and environmental problems rapidly change in ways that cannot be perfectly predicted.
- **Research in forest production planning should focus on the development of growth models that are useful when stochastic optimal control theory is applied.**
- **Since biological production takes considerable time, it is very important to create options to sequentially adjust the production to new relative prices, growth conditions, ecological problems and possible damages caused by parasites, fire or storms.**
- In particular, valuable options can be obtained via mixed species stands. When several species are available in the young stands, the species mix can sequentially be adapted to changing product prices, costs and growth conditions.

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