ECN 275/375 – Natural resource and environmental economics
12:15-15:15 April 10, 2025

All help aids allowed except assistance from others.
This test consists of 3 questions, for a total score of 100 points.
All questions are to be answered. You may answer in English or Norwegian.

In the case that you find a question unclear, or you are uncertain about what is meant, state the extra assumptions you need to be able to answer the question.

This test has been designed to limit the benefits of using Chat GPT and similar artificial intelligence tools. If AI use is detected beyond reasonable doubt, unreported use leads to a score of zero. Students can use AI tools if they self-report such use at a cost: A question with self-reported AI use reduces the score by 40%.

When I submit my answers on this test, I confirm that I have worked alone on my answers and not cooperated with others. I am aware that cooperation with others is to be considered an attempt or a contribution to cheat.
I am aware of the consequences of cheating, cfr. academic regulations for NMBU.

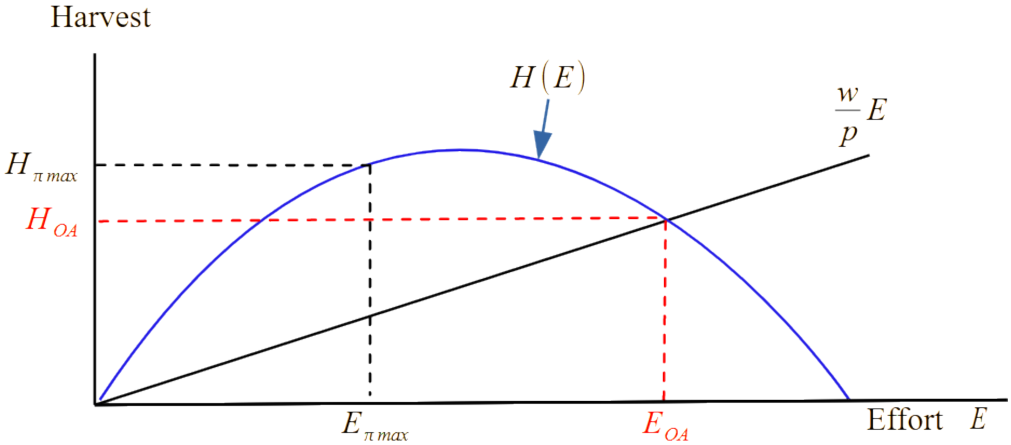
Your name: NN (+ ECN 275 or ECN 375)

Question 1 (30 points – 10 points for each sub-question a-c)

An open access fishery as illustrated below has the following solutions:

- the profit maximizing effort level: $E_{\pi max}$
- the open access effort level: E_{OA}

when $\frac{w}{p}$ is the real wage.



(a) Write down the profit function of this fishery and solve for the profit maximizing and show the condition for open access effort levels for this fishery.

Answer: The profit function: $\pi(E)=TR(E)-TC(E)=p\,H(E)-w\,E$

The profit maximizing effort, $E_{\pi max}$: $\frac{\partial H(E)}{\partial E}=p\,H'(E)-w=0 => H'(E)=\frac{w}{p}$

The open access solution is found at the effort level, E_{OA} , such that the profits (rents) from the fishery are zero, i.e. $\pi(E_{OA})=p\,H(E_{OA})-w\,E_{OA}=0$.

(b) The figure starting this exercise shows that the harvest level that maximizes the profits (rents) from the fishery is greater than the open access harvest level, i.e. $H_{\pi\,max} > H_{OA}$: (i) When this is a case, explain why an aggregate harvest quota $\bar{H} = H_{\pi\,max}$ when individual quotas are non-tradable may not reduce efforts to the profit maximizing level $E_{\pi\,max}$. (ii) Why could tradable quotas still work?

Answer: (i) Because the restriction is non-binding as $H = H_{\pi\,max} > H_{OA}$. Due to zero profits (rents) at E_{OA} , fishing efforts may still decline. Reason: as fishing vessels are retired, there are no rents to justify investments in new boats. This effect will be limited once efforts decline as fishing vessels are retired, there will be rents. Once these rents are sufficiently high to justify investments in new boats, rents will cease to increase.

Remark: this corresponds to the difference between entry and exit prices in ordinary markets.

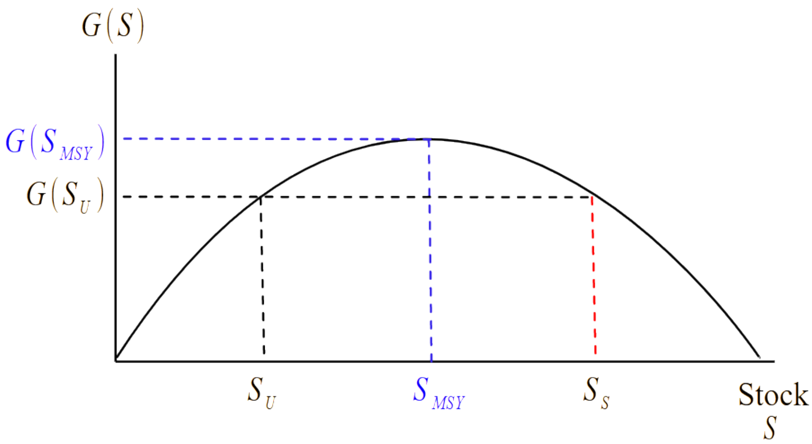
Answer: (ii) Tradable quotas may still work for the following reason. As rents are zero, the costs of acquiring (buying) quotas will be low. Buyers of these quotas can utilize these quotas to maintain zero rents in the short run. This enables buyers and those remaining in the fishery to buy more quotas. At some point in time, those remaining in the fishery may reduce the amount of quotas they utilize, and rents will increase.

Remark: This is a risky strategy for permit buyers as they then would hold dead capital (= capital not giving any returns) in the short run, which opens for an interesting variant of the "chicken game" (= who holds out long enough to reap future rents).

(c) What are the conditions for this fishery being stable and not threatened by extinction if the net growth function does not decline, for example due to climate change? Explain the reasoning behind your conditions. You may choose to illustrate your solution by a graph.

Answer: Both solutions need to satisfy the condition that the without fishing net growth of the fish stock at the unstable stock level needs to be larger than the harvest level, i.e.:

- For the profit maximizing solution: $H(E_{\pi\,max}, S) < G(S_U)\ \forall\ S < S_U$ where $G(S_U)$ is the without fishing net growth of the fish population at the stock level that defines the unstable harvest equilibrium S_U , and similarly
- for the open access equilibrium: $H(E_{OA}, S) < G(S_U)\ \forall\ S < S_U$.



Remark: The above conditions also secure the stability condition as S_{MSY} is an unstable equilibrium for $H = G_{MSY}$. Note that for any harvest level $H < G_{MSY}$ for $S > S_U$, the size of the fish stock moves to S_S .

Question 2 (30 points – 10 points for each sub-question a-c)

The basic standard single rotation timber harvest model for even aged tree stands when replanting occurs at the end of the rotation can be written as: $\pi_T^E = \left(P_T S_T - C_T^E - k_T\right)e^{-Tr}$, where superscript E indicates an even aged tree stand. For a tree stand that reaches its optimal rotation age, T, next year, the discounted profits becomes $\left(P_1 S_1 - C_1^E - k_1\right)e^{-r}$. Similarly, a stand that reaches its optimal rotation age, T, in two years time is then written as: $\left(P_2 S_2 - C_2^{\hat{E}} - k_2\right)e^{-2r}$.

Let there be $T = \tau$ stands where $t = 1, 2, \ldots, \tau$ also indicates age to harvest maturity. The net present value of T equally large stands (for simplicity 1 hectare large) where t is the time before each stand reaches harvest maturity can now be written as:

$$NPV^E = \sum_{t=1}^{\tau} \left(P_t S_t - C_t^E - k_t\right)e^{-tr}$$

- r = the risk-free interest rate,
- P_t = the per volume timber price at the optimal rotation age
- S_t = the timber volume at the optimal rotation age,
- C_t^E = the even aged stand costs of harvesting S_t on a one hectare clear-cut, and
- k_t = the costs of replanting per hectare after the tree harvest.

A forest owner considers select (locked) harvesting, i.e. cutting an equivalent timber volume on a larger area to produce the same volume of timber to avoid for example loss of habitat for certain species from clear-cuts. To simplify matters we assume that the optimal rotation age, $T = \tau$, is the same for select harvesting and clear-cuts. Note that for locked harvests there are no replanting costs, i.e. $k_t = 0$. However, tree harvesting costs are higher for two reasons: First, locked harvests require harvesting over a larger acreage, and second due to damages on remaining trees.

(a) (i) Write down the profit function per harvested tree volume for a randomly chosen time, $1 < t \leq \tau$, for locked harvesting when $C_t^L > C_t^E$. Explain your reasoning for the chosen locked harvest profit function for time t, π_t^L .

(ii) How large are the discounted maximum extra costs to make locked harvesting equally profitable as even stand harvesting for a randomly chosen time, $1 < t \leq \tau$? Show your calculation(s).

Answer (i): My formulation: $\pi_t^L = \left(P_t S_t - C_t^L\right)e^{-tr} = \left(P_t S_t - \left(m + C_t^E\right)\right)e^{-tr}$, where m is the extra harvesting costs from locked harvesting, and there are no replanting costs.

Answer (ii): With my formulation: $\pi_t^L - \pi_t^E = \left(P_t S_t - \left(m + C_t^E\right)\right)e^{-tr} - \left(P_t S_t - C_t^E - k_t\right)e^{-tr}$ which implies $m = k_t$.

(b) Suppose net grazing benefits, B_t , for even aged stands lasts for β years after the clear-cut for game species like moose, i.e. grazing benefits occurs early in the rotation. What is the size of these benefits for a randomly chosen plot indexed t. Hint: Hunting benefits could last for the entire duration of a single rotation, i.e. $t + \beta \leq \tau$, or for only parts of the rotation when $t + \beta > \tau$. Note that is the single rotation optimal time for harvesting (clear-cut). Explain your reasoning and show your calculations.

Answer: With T even aged harvested areas the net benefit for an area harvested in year t=F (full benefit for area t) when $F + \beta \leq \tau$, profit increase equals $\Delta\pi_t^F = \int_{t=F}^{\beta} B_t e^{-rt}\,dt$. For $F + \beta > \tau$ (partial benefit for area t) the profit increase equals $\Delta\pi_t^\tau = \int_{t=F}^{\tau} B_t e^{-rt}\,dt$.

(c) What are the differences in hunting benefits between even aged tree stand management and locked harvest management from (b) under a multiple rotation model? Explain verbally.

Answer: First, all (moose) hunting benefits carry over to the next rotation as the restriction $F + \beta > \tau$ no longer applies. Second, the rotation age is shortened (a well-known result from multiple rotation models).

Question 3 (40 points – 10 points for each sub-question a-d)

Fossil fuel reserves are likely to last longer than the time it takes under current greenhouse gas (GHG) emissions to reach the accumulated greenhouse gas emission restriction (the climate budget) associated with for example a 2 degrees climate target.

(a) Explain why this allows you to drop the fossil fuel reserve restriction in a model with the objective to maximize welfare for a finite time T years to reach the 2 degrees climate target? Instead, you need to replace the resource constraint by a GHG budget constraint. Why?

Answer: When fuel reserves last longer, the fuel reserve restriction can be omitted in this finite time model as its shadow price is zero. The reason you need to replace the standard resource constraint by an accumulated GHG emission constraint is that it limits society's GHG emission causing activities (Z_t in my notation).

(b) Formulate a finite time objective function for a model with both consumer and production externalities. State the appropriate choice variables for the management of greenhouse gas emissions, and explain what these choice variables represent. Also, explain any important parameters in this objective function.

Answer: $$\underset{\{C_t, A_t, V_t\}}{MAX} W = \underset{\{C_t, A_t, V_t\}}{MAX} \int_{t=0}^{T} U(C_t, E_C(A_t)) e^{-rt}\,dt$$

The choice variables are total consumption (C_t), accumulated emissions (A_t), and expenditures (V_t) for reducing the consumption externality $E_C(A_t)$. In addition, there is the parameter r, the risk-free interest rate. Note that the production externality does not appear in the objective function, but enters in the capital change restriction.

(c) (i) Formulate the typical constraints needed for a model with both consumer and producer externalities caused by accumulated GHG emissions. From (a) it follows that it is not necessary with a standard resource constraint for T years. This standard constraint is therefore replaced by an accumulated emission constraint. Explain the terms entering the constraints.

(ii) Express the constrained maximization problem as the current value Hamiltonian specification of the objective function with shadow prices (Lagrangian multipliers) for each of the constraints you have listed. Explain why the shadow price on the GHG budget can be replaced by the price of GHG emissions.

Answer (i): The constraints needed in this model are:

$\dot{S}_t = -A_t$ (GHG remaining budget, it replaces the ordinary resource stock constraint)

$\dot{A}_t = M(Z_t) - \alpha A_t - F(V_t)$ (stock pollutant accumulation change)

$\dot{K}_t = Q(K_t, R_t, E(A_t)) - C_t - V_t$ (capital change)

Explanation of terms in the constraints:

- $\dot{S}_t$ change in the remaining GHG accumulated budget,
- Z_t GHG emissions caused by economic activity,
- $\dot{A}_t$ time change (derivative) in the accumulated stock pollutant A_t,
- $M(Z_t)$ instantaneous emissions from economic activity, Z_t,
- α self cleaning factor (natural decay),
- $F(V_t)$ impacts from policy on accumulated emissions for a given policy expenditure level V_t,
- $\dot{K}_t$ production capital change,
- $Q(K_t, Z_t, E_P(A_t))$ the value of production from man-made capital K_t, GHG-causing production activity Z_t, and the production externality $E_P(A_t)$.

Answer (ii): The current value Hamiltonian:

$$
\begin{aligned}
H = {} & U(C_t, E(A_t)) \\
& + \rho_t(-A_t) && \text{(GHG budget constraint)} \\
& + \lambda_t(M(Z_t) - \alpha A_t - F(V_t)) && \text{(stock pollutant accumulation constraint)} \\
& + \omega_t(Q(K_t, Z_t, E(A_t)) - C_t - F(V_t)) && \text{(capital change (net investment) constraint)}
\end{aligned}
$$

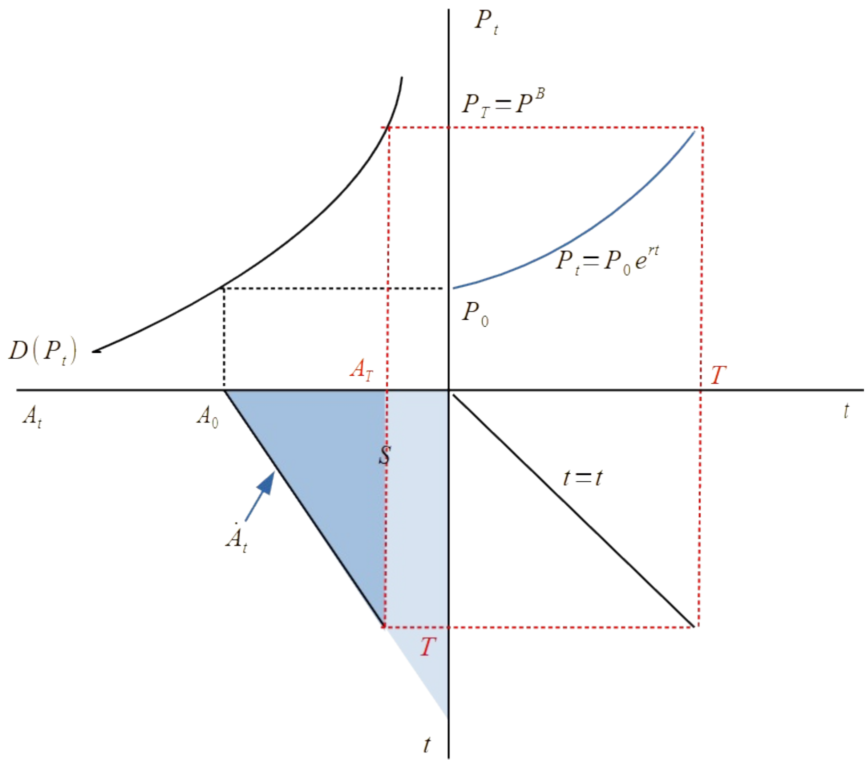
The shadow price, $\rho_t(-A_t)$, on the GHG emission constraint, $\dot{S}_t = -A_t$, can be replaced by the market (EU ETS) price P_t because it represents the opportunity costs of climate gas emissions. Note that this price could also be a GHG emission tax – it also needs to follow a Hotelling price path.

(d) Simplify the Hamiltonian you formulated in (c) to only contain the accumulated GHG gas constraint, i.e. as $H = U(C_t, E_C(A_t)) + P_t(-A_t)$. (i) Explain why this simplification is problematic?

(ii) Suppose that this simplification is unproblematic. Draw a "four corners" graph that captures the effects of this simplified Hamiltonian when a backstop technology arrives rendering GHG emitting production, Z_t, obsolete as the new technology makes net emissions less than zero. Assume that the backstop technology arrives with certainty at time T with a certain price P^B for the substitute of Z_t. Explain your reasoning behind the graph.

Answer (i): The production externality affects overall production negatively, which affects consumption possibilities. Hence, dropping the pollution accumulation and capital change constraints is problematic.

Answer (ii): With certain arrival of the backstop technology at time T with the certain price, P^B, owners of polluting production factors may seek to fully devour the GHG budget at time T. This introduces a choke price for the GHG emission budget equal to the backstop price P^B for the GHG emission free substitute. Recall that the choke price is the price where the demanded quantity, here the GHG emission causing activities, is zero. That implies the use of GHG emission inputs $Z_T = 0$, and that the demand curve meets the price axis at $P^B = P_T$.



Remark: At the time the arrival of the backstop technology and it price is known with certainty, i.e. at t=0, the initial price of accumulated emissions falls (not drawn in the graph), and the Hotelling price path follows the standard rule: $P_t = P_0 e^{rt}$.

Note that in this case the backstop technology arrives before the climate budget was exceeded. As accumulated emissions also cause welfare losses directly through the consumption externality $E_C(A_t)$, and indirectly through the production externality $E_P(A_t)$, the accumulated GHG emissions will not continue to grow. Instead, they decline due to the self cleaning effect αA_t . Suppose the backstop technology arrives later than what is consistent with the budget holding, society may have a difficult choice: welfare losses from expanding the GHG budget or welfare losses from spending more funds on reducing accumulated GHG emissions by increasing funding of abatement measures.