Supplementary Information : The what, when, and how of translating knowledge to action in nature-society systems for sustainability

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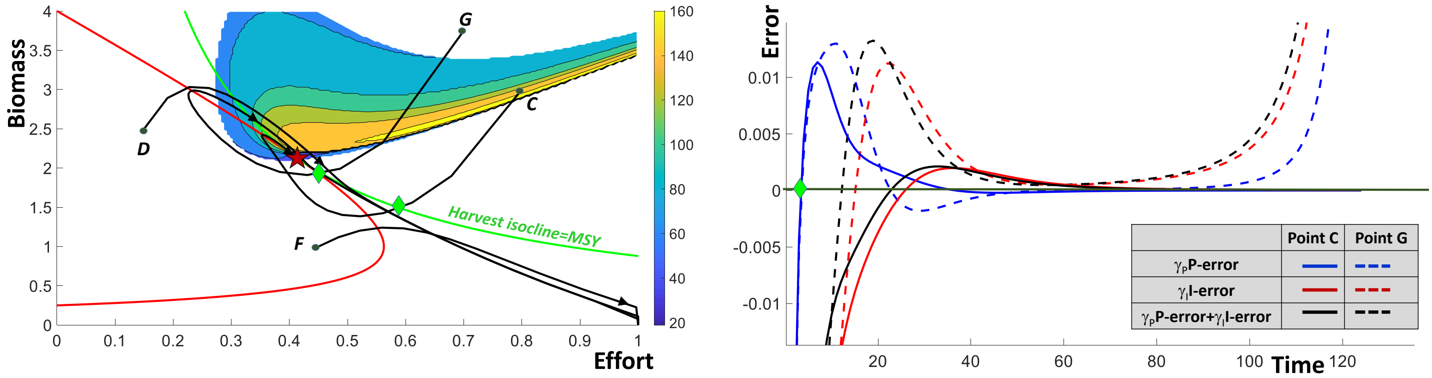
Using a PI-controller for natural resource management

The case discussed in the main text based on the control law given by Equation 4 (summarized in Figure 1) is purely a proportional controller ($\gamma_I = 0.0$). Here we analyze the case assuming harvest is observable (compare with Figure 1c) and both present and past information are used, i.e. $\gamma_P = 0.05; \gamma_I = 0.02$. The shape of the controllability set shown in Figure 1a is completely different than the sets obtained in the P-controller case (cf. Figure 1c) . The integral term stores the history of errors and fundamentally changes the controllability of the system. Such memory of past errors may have a positive or a negative effect on controllability depending on the initial states because of the dynamics of the system. For instance, point C was out of controllability set with only a P-controller whereas keeping error history in the decision-making processes enables the system to be controlled to reach the target (Figure 1a). Note that point G is not controllable with a PI controller because the sum of errors is too large, pushing the system to overshoot the target. This is is due to the "inertia" caused by the I-error as shown in Figure 1b. The blue solid and dashed curves show the P-error for initial points C, and G, respectively. Both start negative and become positive very quickly (crossing zero at the green diamond). The red curves show the corresponding I-errors. For initial point C, the integral error remains negative for quite some time and only becomes slightly positive after time 25, well after the proportional error has begun to decline. From point G, on the other hand, The integral error increases more quickly, becoming positive closer to time 15 while the proportional error is much higher. The total error, and thus the rate of change of the policy is shown by the black curves. For point G (dashed line), the error peaks at around time 20 with a magnitude multiple times higher than for point C which peaks at a much lower level and later. For initial condition C, the error eventually goes to zero and the system eventually stabilizes. For initial condition G, the control response eventually does drive the error down, but never quite to zero. Note that the P-error is below zero for quite some time but the integral error remains positive and makes the net effect positive. Present information that says effort should decrease cannot overcome the inertia of past information that says it should increase. This cases illustrates the importance of forgetting, and just how complicated, and non-intuitive it is to choose the gains for PID controllers.

Dynamics of ICU patients in France

In Figure 2, we plot the number of patients in intensive care units over time (data extracted from data.gouv.fr) in blue overlain with the national lockdown policies with the red vertical lines (note that a combination of more or less restrictive measures were carried out throughout the pandemic which are not reported in this Figure). This data illustrates the potential impact of changing the weights of PID controller as more information becomes available. As described in the main text, the first lockdown (mainly a P-controller) may have extended too long. The second lockdown was shorted as estimates of R_0 were used (a PD-controller). The third lockdown response incorporated past data as well (a full PID controller) and the lockdown very early (in terms of numbers of ICU patients). This case illustrates the role of learning and new information that can be used to dynamically adjust PID controllers.



a - PI controller

b - Error dynamics

Fig. 1 Case of PI controller. Panel a, adding an integral controller yields a memory of past states that may improve the controllability of the system (point C) or not (G point). Note that the green diamond represents the time where both trajectories cross the harvest isocline in Figures 1-a and 1-b. In Panel b, the errors are represented. When the black line is below 0, effort is decreasing and effort increases when the black line is above 0.

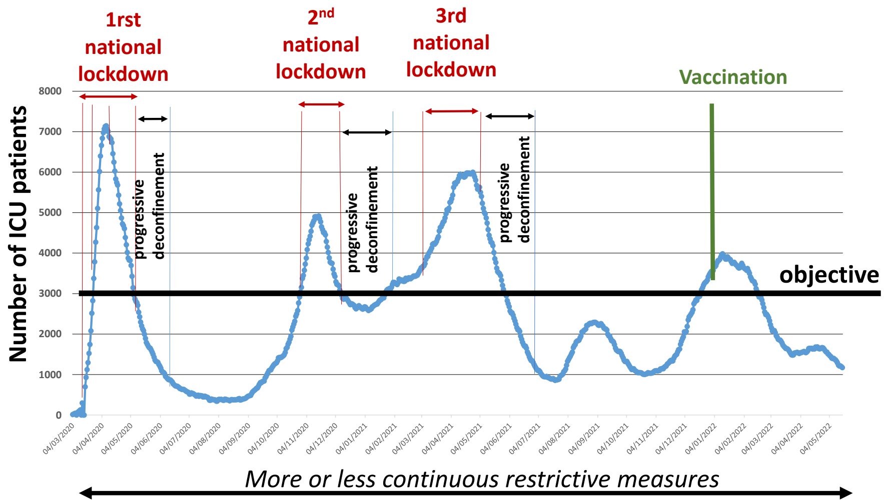


Fig. 2 Dynamics of covid in France with the main restrictions.

Analysis of PID errors on climate dynamics

For Figure 4a, we normalized the errors by the maximum error reached during the reference scenario. For illustrating the effects of P-, I- and D-error, we tested different values of the P-, I- and D-gains. In order to have the same importance for the three errors, we first normalized the gains by the mean respective errors obtained during the reference scenario and we then divided them by 100 to avoid extremely fast dynamics. Results are reported in Table 1. The results show that policies based on D-error are favored. In Figure 4b, curves with best PID combination (rank 1) have been plotted.

P-gain	I-gain	D-gain	CO2-based policy ranking (C02 peak, ppm)	Economic-based policy ranking (C02 peak, ppm)
1	1	1	4 (455)	4 (631)
1	1.1	0.9	7 (459)	7 (635)
1	0.9	1.1	1 (451)	1 (627)
0.9	1	1.1	2 (451)	2 (628)
0.9	1.1	1	5 (455)	5 (632)
1.1	0.9	1	3 (454)	3 (630)
1.1	1	0.9	6 (459)	6 (634)

Table 1 CO2 peak according different values of the gains and the ouput-based policy