<u>Supplemental Material to Accompany Publication of</u>

The Green Paradox, A Hotelling *Cul de Sac*

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Table A: Sensitivity of Base Case Results to High Development Cost (cf. Table 2 of the text)

Background assumptions and parameter values: Oil price = $100/barrel, annual variable cost = $40 per barrel of production plus 2% of capital investment, interest rate = 8%, original oil-in-place = 300 million barrels, capital investment = $60,000 per initial daily barrel of production, lambda (EOR factor) = 2.5. No income tax or other fiscal burdens are imposed besides the royalties described below

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
	initial royalty rate	royalty growth rate	extraction rate	onset of EOR	initial prod	ultimate recovery	end of life	NPV company profit	NPV govt. revenue	company share of max rents	overall rent capture[1]	PV cost per barrel of reduced recovery[2]
scenario	%	%	%	year	mm bbl	mm bbl	year	$ mm	$ mm	%	%	$/bbl
No Royalty												
1	0.00%	0%	5.5%	18	5.50	148	58	$1,763	$0	100%	100%	na
Constant Royalty												
2	25.33%	0%	4.0%	31	4.00	134	78	$721	$881	41%	91%	$11.50
Rapidly Rising Royalty												
3a	17.00%	8%	4.5%	na[3]	4.50	50	15	$472	$848	27%	75%	$4.52
3b	12.00%	10%	5.0%	na[3]	5.00	56	16	$635	$773	36%	80%	$3.86
Rapidly Falling Royalty												
4a	49.70%	-8%	3.5%	20	3.50	164	85	$730	$863	41%	90%	∞
4b	55.00%	-10%	3.5%	19	3.50	167	85	$755	$844	43%	91%	∞
Slowly Rising Royalty												
5a	22.45%	1%	4.5%	na[3]	4.50	91	53	$740	$882	42%	92%	$2.47
5b	19.20%	3%	4.5%	na[3]	4.50	78	33	$713	$881	40%	90%	$2.41
5c	16.27%	5%	5.0%	na[3]	5.00	71	24	$699	$882	40%	90%	$2.36
Slowly Falling Royalty												
6a	27.37%	-1%	4.0%	27	4.00	143	83	$742	$881	42%	92%	$27.92
6b	35.11%	-3%	3.5%	23	3.50	156	85	$691	$881	39%	89%	∞
6c	41.29%	-5%	3.5%	22	3.50	159	85	$698	$881	40%	90%	∞

Notes:
1 Realized mineral rents, ignoring the social cost of emissions.
2 Cost reckoned as mineral rent lost due to impact of royalty.
3 Enhanced oil recovery not economically feasible.

Table B: Sensitivity of Base Case Results to Low Oil Price (cf. Table 2 of the text)

Background assumptions and parameter values: Oil price = $60/barrel, annual variable cost = $20 per barrel of production plus 2% of capital investment, interest rate = 8%, original oil-in-place = 300 million barrels, capital investment = $40,000 per initial daily barrel of production, lambda (EOR factor) = 2.5. No income tax or other fiscal burdens are imposed besides the royalties described below. All royalty schedules are calibrated to capture 33% of maximal rents.

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
	initial royalty rate	royalty growth rate	extraction rate	onset of EOR	initial prod	ultimate recovery	end of life	NPV company profit	NPV govt. revenue	company share of max rents	overall rent capture[1]	PV cost per barrel of reduced recovery[2]
scenario	%	%	%	year	mm bbl	mm bbl	year	$ mm	$ mm	%	%	$/bbl
No Royalty												
1	0.00%	0%	5.5%	18	5.50	148	58	$1,176	$0	100%	100%	na
Constant Royalty												
2	15.76%	0%	5.0%	24	5.00	137	64	$761	$392	65%	98%	$2.09
Rapidly Rising Royalty												
3a	8.80%	8%	5.5%	na[3]	5.50	74	24	$686	$392	58%	92%	$1.32
3b	8.18%	10%	5.5%	na[3]	5.50	68	20	$645	$392	55%	88%	$1.74
Rapidly Falling Royalty												
4a	33.59%	-8%	4.0%	19	4.00	162	80	$724	$392	62%	95%	∞
4b	38.17%	-10%	4.0%	19	4.00	162	80	$724	$392	62%	95%	∞
Slowly Rising Royalty												
5a	14.49%	1%	5.0%	26	5.00	131	61	$754	$392	64%	97%	$1.76
5b	13.06%	3%	5.0%	na[3]	5.00	89	43	$716	$392	61%	94%	$1.15
5c	10.63%	5%	5.5%	na[3]	5.50	84	32	$722	$392	61%	95%	$0.97
Slowly Falling Royalty												
6a	18.27%	-1%	4.5%	23	4.50	145	72	$743	$392	63%	97%	$13.67
6b	21.50%	-3%	4.5%	21	4.50	151	73	$751	$392	64%	97%	∞
6c	27.24%	-5%	4.0%	20	4.00	160	81	$720	$392	61%	95%	∞

Notes:
1 Realized mineral rents, ignoring the social cost of emissions.
2 Cost reckoned as mineral rent lost due to impact of royalty.
3 Enhanced oil recovery not economically feasible.

Table C: Detailed Results, Full-Cycle Oil Field Exploration, Development and Extraction with Dynamic Royalty and Trending Price

Background assumptions and parameter values: Oil price = \$100/barrel, annual variable cost = \$20 per barrel of production plus 2% of capital investment, interest rate = 8%, original oil-in-place Ω is stochastic (75, 300, 2,250 million barrels) with conditional probabilities (50%, 35%, 15%). Probability of dry hole on initial trial = 65%. Cost of exploratory well = \$75 million, development capital investment = \$40,000 per initial daily barrel of production, lambda (EOR factor) = 2.5. No income tax or other fiscal burdens are imposed besides the royalties described below.

If a dry hole is drilled (with assumed probability 65% at the first attempt), the probability that there is a reserve is reduced according to Bayes' rule. As more dry holes are drilled, the probability of a discovery decreases until ultimately the search is abandoned. The exploration model is described fully in Smith (2005, 2014). Table C presents results based on the assumption that the driller's prior belief is strong and not easily shaken by a dry hole.

All scenarios shown in the table are calculated using price trajectories with qualitative properties predicted by the green paradox, and with tax regimes calibrated to capture 50% of the maximal rent available in each specific price scenario. These scenarios examine regimes with constant, increasing and decreasing taxes. According to the green paradox an *increasing* tax causes the initial price to be lower and initial output to be higher than when there is no tax; over time the equilibrium price increases more quickly. In keeping with this prediction, a 3% increase in the tax is assumed to induce a rate of price rise of 2% (> 1.5%).[1] The opposite holds for a tax decreasing at 3%: output increases early on and price rises more slowly, at an assumed rate of 1% in our tables. For comparability of tax effort (meaning that for each price scenario the government captures 50% of potential mineral rents) the increasing tax must start lower and the decreasing tax higher.

Scenario X6 attempts to hold some variables constant in order to make valid comparisons, but there are several divergences – in rents and consequently in incentives, in damages, etc. They display some instances of a *strong green paradox*, defined as a greater present value of emissions with a tax than without. (See columns 23-28.) These strong effects are concentrated at the low rate of discount, *viz*. the 1.4% recommended in the Stern (2006) *Review*, and for the decreasing tax. Perhaps ironically, the strong paradox arises when the discount rate is low, as may be preferred by environmentalists. The reason is that there is greater recovery under the decreasing tax, almost as much as with no tax but well into the future. The greater future emissions are only lightly discounted, at 1.4%.

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[1] This rate is lower than the discount rate of 8% and the theoretic work on the green paradox has a similar prediction. Our focus is on the policy implications of a realistic tax scenario and realistic discount rates, in view of our findings about rates of increase of the tax at and above 8%.

Table C, Panel 1 (optimal exploration and development under various tax/price scenarios)

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
	initial royalty rate[7]	initial price	price growth rate	royalty growth rate	extraction rate	expected initial prod[1]	onset of EOR	expected ultimate recovery[1]	end of life	max explo wells	recovery factor given discovery	expected NPV company profit[1]
Scenario	%		%	%	%	mm bbl	year	mm bbl	year	#	%	$ mm
X1*	0.00%	$100	-2%	na	9.4%	7.32	na	73	29	3	31.3%	$1,758.0
X1a	40.36%	$100	-2%	-3%	6.1%	4.75	na	72	40	3	30.7%	$634.0
X1b	31.92%	$100	-2%	0%	6.6%	5.14	na	70	33	3	29.7%	$682.0
X1c	25.58%	$100	-2%	3%	7.2%	5.60	na	64	23	3	27.3%	$707.0
X2*	0.00%	$100	-1%	na	8.0%	6.35	12	119	38	4	49.7%	$2,075.0
X2a	44.40%	$100	-1%	-3%	5.3%	4.13	17	117	55	3	50.0%	$724.0
X2b	35.19%	$100	-1%	0%	6.4%	4.98	na	73	41	3	31.0%	$720.0
X2c	27.31%	$100	-1%	3%	7.2%	5.60	na	67	26	3	28.7%	$767.0
X3*	0.00%	$100	0%	na	7.5%	5.95	10	132	44	4	55.3%	$2,499.0
X3a	49.00%	$100	0%	-3%	4.9%	3.81	15	131	74	3	56.0%	$867.0
X3b	34.14%	$100	0%	0%	5.9%	4.59	16	118	55	3	50.3%	$962.0
X3c	30.15%	$100	0%	3%	7.1%	5.53	na	67	27	3	28.7%	$780.0
X4*	0.00%	$100	1%	na	7.2%	5.71	10	137	55	4	57.3%	$3,024.0
X4a	55.43%	$100	1%	-3%	4.4%	3.42	14	139	85	3	59.3%	$1,011.0
X4b	35.77%	$100	1%	0%	5.5%	4.28	14	130	72	3	56.0%	$1,185.0
X4c	25.89%	$100	1%	3%	7.0%	5.45	16	101	34	3	43.0%	$1,140.0
X5*	0.00%	$100	2%	na	6.8%	5.40	9	146	69	4	61.0%	$3,670.0
X5a	60.66%	$100	2%	-3%	4.1%	3.19	13	143	85	3	61.3%	$1,249.0
X5b	37.68%	$100	2%	0%	5.2%	4.05	13	137	85	3	58.7%	$1,457.0
X5c	24.92%	$100	2%	3%	6.7%	5.22	13	115	38	3	49.0%	$1,493.0
X6a*	0.00%	$110	1.0%	na	7.5%	5.95	9	140	52	4	58.7%	$3,615.0
X6a	55.81%	$110	1.0%	-3%	4.7%	3.66	13	140	85	3	60.0%	$1,250.0
X6b*	0.00%	$100	1.5%	na	7.0%	5.55	9	143	60	4	60.3%	$3,332.0
X6b	36.10%	$100	1.5%	0%	5.4%	4.20	13	136	82	3	58.0%	$1,343.0
X6c*	0.00%	$90	2.0%	na	6.4%	5.08	10	144	75	4	60.3%	$3,033.0
X6c	23.13%	$90	2.0%	3%	6.3%	4.90	13	117	40	3	50.0%	$1,274.0

Table C, Panel 2 (deadweight loss and economic damages from emissions)

(1)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)
							compare falling to rising royalty			emission damages ($ million) given: $25/bbl + 1.5% p.a. discounted at:		
	expected NPV govt. revenue[1]	govt. take	govt. share of max rents	company share of max rents	overall rent capture[2]	PV cost per Barrel of reduced recovery[3]	initial prod.[4]	total prod.[4]	expected NPV company profit[4]			
Scenario	$ mm		%	%	%	$/bbl	%	%	%	1.4%	6.0%	8.0%
X1*	$0.0	0%	0%	100%	$1,758	na				$ 1,802	$ 1,211	$ 1,048
X1a	$959.0	60%	55%	36%	90.6%	$ 90.16	85%	112%	90%	$ 1,764	$ 1,034	$ 862
X1b	$959.0	58%	55%	39%	93.3%	$ 31.37				$ 1,714	$ 1,057	$ 890
X1c	$959.0	58%	55%	40%	94.8%	$ 9.67				$ 1,568	$ 1,047	$ 901
X2*	$0.0	0%	0%	100%	$2,075	na				$ 2,921	$ 1,604	$ 1,300
X2a	$1,115.0	61%	54%	35%	88.6%	$ 146.58	74%	175%	94%	$ 2,906	$ 1,285	$ 989
X2b	$1,115.0	61%	54%	35%	88.4%	$ 5.23				$ 1,791	$ 1,059	$ 884
X2c	$1,115.0	59%	54%	37%	90.7%	$ 3.72				$ 1,638	$ 1,069	$ 914
X3*	$0.0	0%	0%	100%	$2,499	na				$ 3,253	$ 1,728	$ 1,386
X3a	$1,323.0	60%	53%	35%	87.6%	$ 297.12	69%	195%	111%	$ 3,262	$ 1,334	$ 1,010
X3b	$1,323.0	58%	53%	38%	91.4%	$ 15.21				$ 2,925	$ 1,351	$ 1,053
X3c	$1,323.0	63%	53%	31%	84.2%	$ 6.11				$ 1,651	$ 1,068	$ 911
X4*	$0.0	0%	0%	100%	$3,024	na				$ 3,379	$ 1,728	$ 1,376
X4a	$1,581.0	61%	52%	33%	85.7%	∞	63%	138%	89%	$ 3,463	$ 1,331	$ 994
X4b	$1,581.0	57%	52%	39%	91.5%	$ 40.57				$ 3,245	$ 1,412	$ 1,085
X4c	$1,582.0	58%	52%	38%	90.0%	$ 8.34				$ 2,485	$ 1,348	$ 1,090
X5*	$0.0	0%	0%	100%	$3,670	na				$ 3,599	$ 1,789	$ 1,416
X5a	$1,899.0	60%	52%	34%	85.8%	$ 199.24	61%	125%	84%	$ 3,573	$ 1,339	$ 993
X5b	$1,899.0	57%	52%	40%	91.4%	$ 37.88				$ 3,419	$ 1,437	$ 1,096
X5c	$1,899.0	56%	52%	41%	92.4%	$ 9.00				$ 2,834	$ 1,476	$ 1,176
X6a*	$0.0	0%	0%	100%	$3,615	na				$ 3,447	$ 1,812	$ 1,452
X6a	$1,872.0	60%	62%	34%	96.1%	$ 26.43	75%	120%	98%	$ 3,495	$ 1,398	$ 1,054
X6b*	$0.0	0%	0%	100%	$3,332	na				$ 3,542	$ 1,796	$ 1,427
X6b	$1,733.0	56%	52%	37%	88.6%	$ 42.67				$ 3,379	$ 1,450	$ 1,111
X6c*	$0.0	0%	0%	100%	$3,033	na				$ 3,554	$ 1,698	$ 1,332
X6c	$1,586.0	55%	46%	35%	80.4%	$ 25.09				$ 2,892	$ 1,463	$ 1,156

Table C, Panel 3 (tax-induced reduction in economic damage from emissions and resulting cost-benefit ratio)

(1)	(26)	(27)	(28)	(29)	(30)	(31)	(32)	(33)	(34)	(35)	(36)	(37)	(38)	(39)	(40)	(41)
	emission damages ($ million) given: $25/bbl + 3.0% p.a. discounted at:			change in mineral rents[5] (Γ)	change in emission damages[5] (Δ)						cost per dollar of reduced emission damage[6] (Γ/Δ)					
Scenario	1.4%	6.0%	8.0%		per (23)	per (24)	per (25)	per (26)	per (27)	per (28)	per (23)	per (24)	per (25)	per (26)	per (27)	per (28)
X1*	$ 2,065	$ 1,349	$ 1,156													
X1a	$ 2,158	$ 1,195	$ 978	-$165.0	$ (38)	$ (177)	$ (186)	$ 93	$ (154)	$ (178)	$4.34	$0.93	$0.89	∞	$1.07	$0.93
X1b	$ 2,041	$ 1,206	$ 1,002	-$117.0	$ (88)	$ (154)	$ (158)	$ (24)	$ (143)	$ (154)	$1.33	$0.76	$0.74	$4.88	$0.82	$0.76
X1c	$ 1,795	$ 1,171	$ 998	-$92.0	$ (234)	$ (164)	$ (147)	$ (270)	$ (178)	$ (158)	$0.39	$0.56	$0.63	$0.34	$0.52	$0.58
X2*	$ 3,639	$ 1,895	$ 1,508													
X2a	$ 4,047	$ 1,603	$ 1,193	-$236.0	$ (15)	$ (319)	$ (311)	$ 408	$ (292)	$ (315)	$15.73	$0.74	$0.76	∞	$0.81	$0.75
X2b	$ 2,186	$ 1,220	$ 1,002	-$240.0	$ (1,130)	$ (545)	$ (416)	$ (1,453)	$ (675)	$ (506)	$0.21	$0.44	$0.58	$0.17	$0.36	$0.47
X2c	$ 1,895	$ 1,203	$ 1,018	-$193.0	$ (1,283)	$ (535)	$ (386)	$ (1,744)	$ (692)	$ (490)	$0.15	$0.36	$0.50	$0.11	$0.28	$0.39
X3*	$ 4,121	$ 2,060	$ 1,621													
X3a	$ 4,801	$ 1,693	$ 1,233	-$309.0	$ 9	$ (394)	$ (376)	$ 680	$ (367)	$ (388)	∞	$0.78	$0.82	∞	$0.84	$0.80
X3b	$ 3,994	$ 1,666	$ 1,258	-$214.0	$ (328)	$ (377)	$ (333)	$ (127)	$ (394)	$ (363)	$0.65	$0.57	$0.64	$1.69	$0.54	$0.59
X3c	$ 1,918	$ 1,204	$ 1,016	-$396.0	$ (1,602)	$ (660)	$ (475)	$ (2,203)	$ (856)	$ (605)	$0.25	$0.60	$0.83	$0.18	$0.46	$0.65
X4*	$ 4,386	$ 2,078	$ 1,618													
X4a	$ 5,323	$ 1,712	$ 1,226	-$432.0	$ 84	$ (397)	$ (382)	$ 937	$ (366)	$ (392)	∞	$1.09	$1.13	∞	$1.18	$1.10
X4b	$ 4,619	$ 1,765	$ 1,310	-$258.0	$ (134)	$ (316)	$ (291)	$ 233	$ (313)	$ (308)	$1.93	$0.82	$0.89	∞	$0.82	$0.84
X4c	$ 3,111	$ 1,598	$ 1,266	-$302.0	$ (894)	$ (380)	$ (286)	$ (1,275)	$ (480)	$ (352)	$0.34	$0.79	$1.06	$0.24	$0.63	$0.86
X5*	$ 4,773	$ 2,164	$ 1,672													
X5a	$ 5,568	$ 1,734	$ 1,232	-$522.0	$ (26)	$ (450)	$ (423)	$ 795	$ (430)	$ (440)	$20.08	$1.16	$1.23	∞	$1.21	$1.19
X5b	$ 5,004	$ 1,809	$ 1,331	-$314.0	$ (180)	$ (352)	$ (320)	$ 231	$ (355)	$ (341)	$1.74	$0.89	$0.98	∞	$0.88	$0.92
X5c	$ 3,607	$ 1,771	$ 1,382	-$278.0	$ (765)	$ (313)	$ (240)	$ (1,166)	$ (393)	$ (290)	$0.36	$0.89	$1.16	$0.24	$0.71	$0.96
X6a*	$ 4,408	$ 2,164	$ 1,699													
X6a	$ 5,256	$ 1,782	$ 1,291	-$493.0	$ 48	$ (414)	$ (398)	$ 848	$ (382)	$ (408)	∞	$1.19	$1.24	∞	$1.29	$1.21
X6b*	$ 4,630	$ 2,163	$ 1,681													
X6b	$ 4,879	$ 1,817	$ 1,345	-$256.0	$ (163)	$ (346)	$ (316)	$ 249	$ (346)	$ (336)	$1.57	$0.74	$0.81	∞	$0.74	$0.76
X6c*	$ 4,825	$ 2,074	$ 1,584													
X6c	$ 3,728	$ 1,770	$ 1,367	-$173.0	$ (662)	$ (235)	$ (176)	$ (1,097)	$ (304)	$ (217)	$0.26	$0.74	$0.98	$0.16	$0.57	$0.80

Notes:

1 **Table entries represent expected values across all exploration results.**

2 **Realized mineral rents, ignoring the social cost of emissions.**

3 **Cost reckoned as mineral rent lost due to impact of royalty.**

4 **Outcome with falling royalty relative to outcome with rising royalty.**

5 **Change in mineral rents relative to no royalty scenario.**

6 **Only shaded cells pass cost/benefit test for social welfare.**

7 **Royalty rates calibrated to allow government to capture one-half of potential (pre-tax) rent at development stage.**