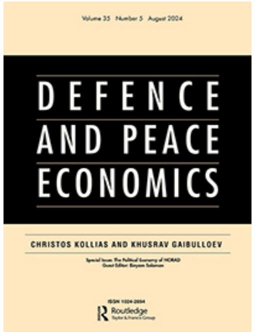

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On Distinguishing Defence Inputs in an Alliance – The Case of NORAD

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ABSTRACT
Our model extends the joint-products models to allow for two types of defence inputs used to produce both an alliance-wide public defence output and a country-specific private output. Distinguishing different defence inputs is particularly appropriate in the case of the North American Aerospace Defense Command (NORAD), as the alliance-wide defence output is produced with two inputs – military technology in the form of sensors and radars and land. These two inputs are complements in the production of the alliance-wide public output. At the same time, the military technology has country-specific private benefits as this can be used by the civilian economy. Our analysis shows that distinguishing between defence inputs may change the predictions of the joint-products model. We derive conditions under which an ally responds to an increase in the defence input by other allies by increasing or decreasing its own contribution of both or only one of the defence inputs.

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Introduction

Our model falls under the general economic theory of alliances. This theory goes back to Olson and Zeckhauser (1966), which considered defence as a pure public good among members of a military alliance. The type of defence Olson and Zeckhauser (1966) had in mind is deterrence, which is based on a credible threat to punish an attack on any of the members of the military alliance. The public goods model of defence is a *one-input, one output model*; one defence input – military expenditures – produces one defence output – an alliance-wide defence output. Given the public good nature of deterrence, allies' military expenditures are suboptimal compared with their Pareto-optimal levels, as allies choose their contribution of military expenditures ignoring the marginal benefits of their contribution on other allies. Thus, allies tend to free-ride on the contribution of other allies. Moreover, the model predicts unequal burden-sharing by allies, with large and rich allies bearing disproportionate burdens compared with small and poor allies.[1]

The joint-products model of defence generalizes the public goods model of alliances. van Ypersele de Strihou (1967) was the first to indicate that military expenditures provide both alliance-wide public good benefits and country-specific private benefits, in the form of political, internal security, and economic benefits. This brought about the joint-products model of defence, which was developed and analyzed, mostly in the context of NATO, by Sandler (1977), Sandler and Forbes (1980), Cornes and Sandler (1984, 1994), Murdoch and Sandler (1982, 1984), Cornes (1993), Conybeare et al. (1994), and Sandler and Hartley (1995).[2] The joint-products model is a *one-input,*

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two-outputs model; one defence input – military expenditures, produces both a country-specific private defence output and an alliance-wide public defence output. The public defence output can be thought of as nuclear deterrence and the country-specific private defence output as protection and internal security. The main prediction of the joint-products model is that, if the private defence and public defence outputs are complements in the Hicksian sense (i.e. an increase in the amount of public output increases the marginal valuation of the private output), then each ally responds to an increase in military expenditures by the other allies by increasing its own military expenditures. The free-riding problem is, thus, less severe relative to the public goods model.

Our model extends the joint-products models to allow for two types of defence inputs. Our model is thus, a *two-inputs, two-outputs model*; two defence inputs are used to produce both an alliance-wide public defence output and a country-specific private output. The importance of distinguishing different defence inputs is apparent in several key alliance examples. In particular, land as a distinct defence input matters critically in the production of the alliance-wide defence output.

First, the U.S. invasion of Iraq from the North in 2003 was severely undermined by Turkey's refusal to grant a land corridor to the forward-ready U.S. forces. While the intervention proceeded, i.e. the technology was not fully of fixed-proportions, lack of land inflicted high costs – financial as well as in terms of the credibility of intervention – by not allowing U.S. troops to be deployed at Iraq's border with Turkey. In this case, land mattered as a distinct input beyond its financial burden. Forward readiness is always a costly proposition but, in this case, troops on ships in particular and in Cyprus waiting for the invasion were heavily costly both in financial terms as well as of morale. Burden-sharing by the reluctant local ally would have reduced costs and fatigue, and it might have made a significant tactical difference. Under the circumstances, land access denial played illustrated the weaker-link technology: 'In contrast to the weakest-link technology, if one agent is not contributing it is still possible to attain positive levels of the public good' (Arce 2001).

Second, the US has several large bases in countries which are traditional and stable allies, such as Japan and Korea. Third, recently, the U.S. has been very active in trying to gain access to land in Kyrgyzstan, Tajikistan and Uzbekistan for bases, some that had been activated during the Afghanistan intervention. Finally, in the case of the bi-lateral North American Aerospace Defense Command (NORAD), the alliance-wide defence output is produced with two inputs – military technology in the form of sensors and radars, and land. In fact, 73% of the long- and 92% of the short-range radars are on Canadian land. These two inputs are complements in the production of the alliance-wide public output. NORAD, thus, represents one of the strongest cases requiring an extension of the standard joint-products model (Charron et al. 2019; Charron and Fergusson 2020).

In the case of the bi-country NORAD alliance, the joint products are generated through the North Warning System (NWS), a system of short- and long-range radar installations across the Canadian Arctic and down the coast of Labrador that constitute the early warning system against incoming missiles. The system, installed in the 1990s, is at the end of its technological life. Moreover, the new political and strategic environment, where an increasingly belligerent Russia that resumed its prodding long-range bomber flights since 2010s has also become a global threat, requires a significant technological modernization of the system in the new threat environment dotted with cruise missiles and hypersonic gliding vehicles (Brockmann and Schiller 2022; Fergusson 2020). Unlike the cruise missiles from the 1980s, the new ones and the gliding vehicles can be launched from afar and can approach North America at such high speeds that they significantly shorten the required detection and response times for a credible deterrent (Corbett 2013). Moreover, the swarming effect (Verklan 2021) they could produce alongside drones could simply overwhelm the existing system. Thus, the new deterrent requires a seamless integration of an effective and resilient detection system with a quick-launch response system (Sherman 2021; Berkok et al. 2022). The modernized NORAD must be designed and built to produce such a deterrent.

An aspect of the Modernized NORAD that received scant attention in literature is the scale and the scope of the investment (Droff and Malizard 2020; Fetterly and Solomon 2021). We can think of the scale as the detection at the origin, which might yield the minimum response time, and the scope in terms of the multi-domain sensors which would require returns to different types of sensors to maximize the resilience and redundancy to be built into the system sensors network (Congressional Research Service CRS 2022; Lamont et al. 2011; Mallory 2018). If, for example, satellite-based sensors become more resilient, then the system might reallocate resources away from, say, land-based to satellite-base sensors (Csenkey and Genest 2021). However, in the meantime, whereas Canada's land may have very low imputed value for NATO, it exhibits high value for NORAD by accommodating the over-the-horizon radars and underwater sensors hence reinforcing resilience and redundancy of the NORAD network. Moreover, under the Modernized NORAD, over-the horizon radars, especially those built significantly further north on the Ellesmere Island will reduce response times. This invokes a discussion of the 2-20 paradigm[3] in the sense that 2% is quite arbitrary though it may be a conventional focal point. Or, maybe, it would have been in an alliances game with payoffs calibrated to weighted contributions to the alliance.

The jointly produced outputs for Canada by such a system as NORAD consist of three distinct components. One component is the infrastructure for detection network installations, including transport and communications, and the continuing installation maintenance currently performed by a native corporation. The 47 radar sites, with all their complexities, are maintained out of five logistics support sites in northern Canada, with a separate system support centre. As with several defence installation operations, this is a public-private partnership (PPP) in that the core defence function of the NWS is run by the joint Canadian and American staff from the system support centre. While the maintenance is an (intermediate) input in the production of the private output, the core function of the support centre is the technological input into the public output. Since the modernized NWS will expand further north, it will require new installations and, hence, further demand for maintenance. Second, the envisaged new system will have to be sufficiently sophisticated for speed, detection and resiliency based on multi-mission (against swarming and different attack vehicles) and multi-domain (for resiliency as well as for accuracy through sensors on land, underwater, on satellites and on aircraft platforms) sensors (RADA, 2020).[4] We note that this second component will generate benefits for both Canada and the U.S. as sensor and communications sectors in both countries are capable to contribute to the modernization of NWS (Jenkins 2013. If the modernized system uses dual-use technologies, it may be possible to generate northern communications systems that will connect northern and native communities to the country as a whole. Finally, the system is likely to include underwater sensors that may jointly produce surveillance and reconnaissance (Brown 2014; Kieley 2021) information which is critical for the security and sovereignty of the Arctic countries, especially in the context of Russia's aggressive presence in the region and China's ambitions for the region. This component contributes to the North American security by observing the maritime traffic in the Northwest Passage and beyond. In fact, beyond the national security benefit for both Canada and the U.S., an added private benefit for Canada could result from a strengthened enforcement of environmental rules on vessels using the passage with better surveillance. However minor, such an environmental regulation of Arctic waters may generate external non-military benefits to the U.S. in terms of marine traffic entering U.S. waters coming out of the Northwest Passage.[5]

Interestingly, the public output generated by a modernized NORAD may not be restricted to the two members of NORAD. Other members of the Arctic Council, minus Russia of course, are members of NATO and, hence, bound by the Article 5 of the Alliance. Whereas they may not be part of NORAD, they benefit from a credible deterrence by virtue of their spatial positions and their proximity to the flightpaths of some Russian missiles launched from afar.

To reiterate, our model extends the joint-products models to allow for two types of defence inputs. Our model is thus a *two-inputs, two-outputs model*; two defence inputs are used to produce both an alliance-wide public defence output and a country-specific private output. As indicated above, distinguishing different defence inputs is particularly appropriate in the case of NORAD, as the alliance-wide defence output is produced with two inputs – military technology in the form of sensors and radars, and land. These two inputs are complements in the production of the alliance-wide public output. At the same time, the military technology has country-specific private benefits as this can be used by the civilian economy.

In what follows, for the sake of readability, we will be referring to the two defence inputs as technology and land, although the reader may substitute other complementary defence inputs for these. Thus, in our model, the alliance-wide public defence output is produced with both technology and land; the country-specific private output is produced with technology. Our choice of defence inputs is, however, not accidental. In the case of NORAD, the alliance-wide defence can only be produced with both land and technology; land and technology are both critical and complementary inputs in the production of the alliance-wide defence. If neither ally contributes land, the alliance-wide defence cannot be produced because the radars cannot be installed; if neither ally contributes technology, the alliance-wide defence cannot be produced because there are no radars to be installed.[6]

Our analysis shows that distinguishing between defence inputs may change the predictions of the joint-products model. To better understand the intuition behind our results, the reader has to keep in mind (1) the distinction between the two inputs and the two outputs and (2) the fact that the two inputs are complements in the production of the public output. Land[7] is an input which contributes only to the production of the alliance-wide public output; technology is an input which contributes to the production of both the alliance-wide public output and the country-specific private output. Thus, on the one hand, allies' contributions of land are similar to contributions to a public good – allies have incentives to free-ride on the other's contribution; on the other hand, allies contributions of technology are similar to contributions to a joint-product – allies' response to the other's contribution can go either way, depending on whether the public and the private outputs are complements in the Hicksian sense. Given the complementarity of land and technology in the production of the public output, the overall effect can go either way as follows.

In particular, we derive conditions under which an ally responds to an increase in the defence input by other allies by increasing or decreasing its own contribution of both or only one of the defence inputs. In particular, we show that an ally, whose technology is less productive in producing the public defence output than the other ally, responds to an increase in the technology contribution of the other ally by decreasing its own contribution of technology and increasing its contribution of land. That same ally responds to an increase in the land contribution of the other ally by decreasing its own contribution of land. If, however, an ally's technology is more productive in producing the public defence output than the other ally, that ally responds to an increase in the technology contribution of the other ally by increasing its own contributions of both defence inputs – technology and land. That same ally responds to an increase in the land contribution of the other ally by increasing its own contribution of land. An increase in an ally's contribution of land may result in an increase, decrease, or no change in the other ally's contribution of technology, depending on the strength of the second-order effects. These results show that the joint-products model with one defence input – military expenditures – does not offer a full picture of allies' responses to other allies changes in defence input contributions. Our model combines features of both the public goods and the joint-products models and, thus, offers a more nuanced analysis of allies' incentives and behaviour in a military alliance.[8]

To better understand the intuition behind our results, one has to keep in mind (1) the distinction between the two inputs and the two outputs and (2) the fact that the two inputs are complements in the production of the public output. Land is an input which contributes only to the production of the alliance-wide public output; technology is an input which contributes to the production of both the alliance-wide public output and the country-specific private output. Thus, on the one hand, allies' contributions of land are similar to contributions to a public good – allies have incentives to free-ride on the other's contribution; on the other hand, allies contributions of technology are similar to contributions to a joint-product – allies' response to the other's contribution can go either way, depending on whether the public and the private outputs are complements in the Hicksian sense.

Given the complementarity of land and technology in the production of the public output, the overall effect can go either way.

The remainder of the paper is organized as follows. Section 2 sets up the model. Subsection 2.1 derives the Nash-Cournot equilibrium conditions, subsection 2.2 determines the comparative static results, and subsection 2.3 presents the results for the specific case when the defence inputs are imperfect substitutes. Section 3 concludes.

The Model

The model consists of two countries or allies, with each ally, $i \in \{A, B\}$ allocating national income, I_i, between a numéraire good, y_i, a pure public defence output, Z, and a private output, x_i, which may or may not be a defence output. Ally i's objective is to maximize the quasi-linear utility function

$$U^i(y_i, x_i, Z) = y_i + V^i(x_i, Z),\ i \in \{A, B\} \tag{1}$$

where y_i is a private numéraire good, x_i is the country-specific private output and Z is the alliance-wide public defence output. We assume throughout that $V^i(\cdot)$ is a continuous, twice differentiable, strictly increasing, and strictly quasi-concave function.

The country-specific private output is produced with defence input n_i

$$x_i = f_i(n_i) \tag{2}$$

with $f_i' > 0$. If we think of the defence input n_i as ally i contribution of military technology, then, once developed, this technology can also be used in the civilian economy of country i to produce the country i-specific private output, x_i.

The alliance-wide public defence output, Z, is produced with two defence inputs, N and M, according to the production function

$$Z = F(N, M) \tag{3}$$

where N and M are produced with the aggregation technologies

$$N = g\left(n_i, n_j\right) \tag{4}$$

$$M = h\left(m_i, m_j\right) \tag{5}$$

with $f_i' = \frac{df_i}{dn_i} > 0$, $F_N' = \frac{\partial F_i}{\partial N} > 0$, $F_M' = \frac{\partial F_i}{\partial M} > 0$, $g_i' = \frac{\partial g}{\partial n_i} > 0$, $g_j' = \frac{\partial g}{\partial n_j} > 0$, $h_i' = \frac{\partial h}{\partial m_i} > 0$, and $h_j' = \frac{\partial h}{\partial m_j} > 0$, for $i, j \in \{A, B\}$, with all functions being continuous and twice differentiable.

Again, defence input, n_i, can be thought of as the ally i's contribution of defence technology (e.g. sensors, radars) and m_i as ally i's contribution of land. Thus, N is the total amount of technology contributions and M is the total amount of land contributions of the two allies. The alliance-wide public defence output, Z, is produced with both technology and land contributions of the two allies.

Ally i' is subject to the resource constraint

$$y_i + p_N n_i + p_M m_i = I_i \tag{6}$$

where p_N and p_M are the prices of defence inputs N and M, and I_i is ally i's income.

In sum, our model is a two-inputs, two-outputs model. Two defence inputs, n_i, which can be thought of as military techonology, and m_i, which can be thought of as land, produce a country-specific private (not necessarily defence) output, x_i, and an alliance-wide public defence output, Z. The alliance-wide public output, Z, can be thought of as deterrence, but the country-specific private output, x_i may be a private civilian output. Our specification breaks down military expenditures into two different defence inputs. Defence input, n_i (military techonology), contributes to the production of both the country-specific output, x_i, and the alliance-wide public defence output, Z. Defence input, m_i (land), on the other hand, contributes only to the production of the alliance-wide public defence output, Z. This differs from the standard joint-products model, which is a one-input, two-outputs model. Our model, thus, combines features of both the joint-products model and the public-good model of alliances.[9]

Nash-Cournot Equilibrium

In a Nash-Cournot equilibrium, each ally chooses the amount of defence inputs, n_i and m_i, to contribute, in order to maximize utility, taking as given the levels of defence inputs, n_j and m_j, chosen by ally j, and subject to the resource constraint:

$$Max_{\{y_i,n_i,m_i\}} y_i + V^i\left(f_i(n_i), F\left(g\left(n_i, n_j\right), h\left(m_i, m_j\right)\right)\right), \text{s.t.} y_i + p_N n_i + p_M m_i = I_i \tag{7}$$

The first-order conditions give

$$f_i^{'} \cdot \frac{\frac{\partial V^i}{\partial x_i}}{\frac{\partial V^i}{\partial y_i}} + F_N^{'} i^{'} \cdot \frac{\frac{\partial V^i}{\partial Z}}{\frac{\partial V^i}{\partial y_i}} = p_N, \tag{8}$$

$$F_M^{'} i^{'} \cdot \frac{\frac{\partial V^i}{\partial Z}}{\frac{\partial V^i}{\partial y_i}} = p_M. \tag{9}$$

The first-order conditions can be re-written as

$$MRS^i_{ny} = f^i_i xy^i + F^i_N i^{'}_{Zy} i = p_N, \tag{10}$$

$$MRS^i_{my} = F^{'}_M i^{'}_{Zy} i = p_M, \tag{11}$$

where MRS^i_{ny} and MRS^i_{my} are ally i's marginal rates of substitution between defence inputs n_i and m_i and the numéraire, y_i, respectively. MRS^i_{ny}, in turn, is equal to a weighted sum of MRS^i_{xy}, the marginal rate of substitution between the private output, x_i, and the numéraire, y_i, on the one hand, and MRS^i_{Zy}, the marginal rate of substitution between the public output, Z, and the numéraire, y_i, on the other hand; the weights are the marginal productivities, $f_i^{'}$ and $F_N^{'} i^{'}$, of input n_i in producing each of the jointly produced outputs, x_i and Z, respectively. Since defence input m_i contributes only to the production of the public defence output, Z, its marginal benefit, given by MRS^i_{my}, is equal to MRS^i_{Zy}, multiplied by its marginal productivity, $F^i_M i^i$ in producing the public defence output, Z. The marginal productivities of the two defence inputs differ for each ally, which allows for allies to have a comparative advantage in supplying one defence input over the other.

The first-order conditions simply say that the defence inputs are supplied up to the point where the marginal benefit of each input, n_i and m_i, equals its marginal cost, p_N and p_M, respectively. The first-order condition with respect to input n_i is, unsurprisingly, the same as the the first-order condition in the standard joint-products model. The first-order condition with respect to input m_i, which contributes to the production of the public good, Z, is new. As we'll see, the presence of this input may change the predictions of the joint-product model.

Comparing the Nash-Cournot equilibrium with the conditions for Pareto optimality

$$f_i^{'} \cdot MRS^i_{xy} + F_N^{'} \cdot g_i^{'} \cdot \sum_{k=1}^{2} MRS^k_{Zy} = p_N \tag{12}$$

$$F_M^{'} \cdot h_i^{'} \cdot \sum_{k=1}^{2} MRS^k_{Zy} = p_M \tag{13}$$

for $i \in \{A, B\}$, makes clear that both Nash equilibrium levels of defence inputs, n_i and m_i, are suboptimal, because each ally chooses these ignoring the effect of its choice on the other ally.

The first-order conditions implicitly define ally i's reaction functions, n_i and m_i, to the defence inputs chosen by ally j

$$n_i = n_i\left(I_i, p_N, p_M, n_j, m_j\right) \tag{14}$$

$$m_i = m_i\left(I_i, p_N, p_M, n_j, m_j\right) \tag{15}$$

for $i, j \in \{A, B\}$, $i \neq j$. The reaction functions show how each ally's demand for defence inputs vary with the other ally's contribution of defence inputs. The comparative statics properties of the reaction functions, (14) and (15), with respect to n_j and m_j, give the slopes of the reaction paths. A negative slope would indicate that each ally reduces its contribution of defence inputs as a reaction to the other ally's increased contribution of defence inputs, giving rise to free-riding. A positive slope, on the other hand, would indicate that each ally increases its contribution of defence inputs as a reaction to the other ally's increased contribution of defence inputs, and, thus, alleviates the free-riding problem. In the standard joint-products model, when the joint *outputs*, x_i and Z, are complements in a Hicksian sense, the slope of the reaction function is positive, and, thus, an increase in one ally's contribution of the defence input will induce the other ally to increase its contribution as well. Our model differs from the standard joint-products model in that the public defence output is produced with two different defence inputs, N and M. In addition, each ally's contribution, n_i, towards N, produces country i-specific private benefits as well.

In the case of the NORAD alliance, as is, undoubtedly, the case with other alliances, the public defence output is produced with land (or other military domains) and other inputs, such as technology (e.g. radars, sensors, etc). Therefore, a realistic assumption is that the defence *inputs N* and M are complements, and, as a result, public defence, Z, is produced with a Leontief technology:

$$Z = F(N, M) = min\{N, M\} \tag{16}$$

The defence inputs, N and M, are aggregated using the functions in Equation 4 and (Equation 5).

The Leontief technology implies that, at the equilibrium,

$$g\left(n_i, n_j\right) = h\left(m_i, m_j\right) \tag{17}$$

which can be solved for $m_i\left(n_i, n_j, m_j\right)$.

Implicit differentiation of (17) with respect to n_i, n_j, and m_j gives

$$\frac{\partial m_i}{\partial n_i} = \frac{g_i^{'}}{h_i^{'}}, \tag{18}$$

$$\frac{\partial m_i}{\partial n_j} = \frac{g_j^{'}}{h_i^{'}}, \tag{19}$$

$$\frac{\partial m_i}{\partial m_j} = \frac{h_j^{'}}{h_i^{'}}. \tag{20}$$

Substituting (17) into the objective function and $m_i\left(n_i, n_j, m_j\right)$ into the budget constraint results in the following optimization problem for ally i

$$Max_{\{y_i, n_i\}} U^i(y_i, x_i, Z) = y_i + V^i\left(f_i(n_i), g\left(n_i, n_j\right)\right), \text{s.t.} y_i + p_N n_i + p_M m_i\left(n_i, n_j, m_j\right) = I_i. \tag{21}$$

The first-order conditions give

$$f_i' \cdot MRS_{xy}^i + g_i' \cdot MRS_{Zy}^i = p_N + p_M \frac{g'_i}{h'_i}. \tag{22}$$

We assume that the second-order condition for this maximization problem holds, that is,

$$\begin{aligned}\Phi \equiv & f_i'' xy^i + g_{ii}'' Zy^i + f_i' \left[f_i' \frac{\partial MRS_{xy}^i}{\partial x_i} + g_i' \frac{\partial MRS_{xy}^i}{\partial Z} \right] + g_i' \left[f_i' \frac{\partial MRS_{Zy}^i}{\partial x_i} + g_i' \frac{\partial MRS_{Zy}^i}{\partial Z} \right] \\ & - p_M \frac{1}{(h_i')^3} \left[g_{ii}''(h_i')^2 - \left(g_i'\right)^2 h_{ii}'' \right] < 0.\end{aligned} \tag{23}$$

where $f_i'' = \frac{d^2 f}{dn_i^2}$, $g_{ii}'' = \frac{\partial^2 g}{\partial n_i^2}$, and $h_{ii}'' = \frac{\partial^2 h}{\partial m_i^2}$.

Comparative Statics Properties

The first-order condition (22) defines $n_i(n_j, m_j)$ as ally i's reaction function to ally j's choice of technology, n_j, and land, m_j. In what follows, we derive the comparative static properties of ally i reaction function by implicit differentiation of the first-order condition, (22), with respect to n_j and m_j in turn. The goal here is to derive the signs of the partial derivatives of the reaction function n_i with respect to n_j and m_j, that is, $sign\left[\frac{\partial n_i}{\partial n_j}\right]$ and $sign\left[\frac{\partial n_i}{\partial m_j}\right]$.

We then use these along with the equilibrium condition (17) to derive $sign\left[\frac{\partial m_i}{\partial n_j}\right]$ and $sign\left[\frac{\partial m_i}{\partial m_j}\right]$.

We first determine $sign\left[\frac{\partial n_i}{\partial n_j}\right]$. Implicit differentiation of (22) with respect to n_j gives

$$\Phi \frac{\partial n_i}{\partial n_j} = -g_j' \left[f_i' \frac{\partial MRS_{xy}^i}{\partial Z} + g_i' \frac{\partial MRS_{Zy}^i}{\partial Z} \right] + p_M \frac{g_{ij}''(h_i)^2 - g_i' g_j' h_{ii}''}{(h_i)^3} - g_{ij} MRS_{Zy}^i \tag{24}$$

This implies that

$$\frac{\partial n_i}{\partial n_j} \left\{ \geq 0 \text{iff}_i' \frac{\partial MRS_{xy}^i}{\partial Z} + g_i' \frac{\partial MRS_{Zy}^i}{\partial Z} \geq p_M \frac{g_{ij}''(h_i)^2 - g_i' g_j' h_{ii}''}{(h_i)^3} - g_{ij}'' MRS_{Zy}^i \right. \tag{25}$$

$$\frac{\partial n_i}{\partial n_j} \left\{ \leq 0 \text{iff}_i' \frac{\partial MRS_{xy}^i}{\partial Z} + g_i' \frac{\partial MRS_{Zy}^i}{\partial Z} \leq p_M \frac{g_{ij}''(h_i)^2 - g_i' g_j' h_{ii}''}{(h_i)^3} - g_{ij}'' MRS_{Zy}^i \right. \tag{26}$$

Equation 25 and (Equation 26) show that, if the second-order effects of changes in the defence inputs on the aggregation technologies, $g_{ij}''$and h_{ii}'' are very small or equal to zero, the discussion of the $sign\left[\frac{\partial n_i}{\partial n_j}\right]$ comes down to the sign of the left-hand sides of these equations. This discussion is similar to that in the case of the joint-products model. This is to be expected since defence input n_i contributes both the production of the private good, x_i, and the public good, Z. Since $\frac{\partial MRS_{Zy}^i}{\partial Z}$ is negative due to diminishing marginal rate of substitution, the sign of the left-hand sides of (25) and (26) depends on the sign of $\frac{\partial MRS_{xy}^i}{\partial Z}$ and the relative magnitude of $\frac{\partial MRS_{Zy}^i}{\partial Z}$ and $\frac{\partial MRS_{xy}^i}{\partial Z}$.

If the private output, x_i, and public output, Z, are complements in the Hicksian sense (that is, the marginal value of the private output x_i increases as more of the public output Z is produced), then $\frac{\partial MRS_{xy}^i}{\partial Z}$ is positive. If the complementarity effect dominates the diminishing marginal rate of substitution effect, then $sign\left[\frac{\partial n_i}{\partial n_j}\right]$ is positive and ally i increases its contribution of defence input n_i in response to an increase in ally j's contribution n_j. However, this result may be reversed if ally i has a high productivity in producing the public output, that is, g_i' is very high, even if the two outputs are complementary; in this case, ally i decreases its contribution of defence input n_i in response to an increase in ally j's contribution n_j.

If, on the other hand, the private output, x_i, and public output, Z, are substitutes in the Hicksian sense (that is, the marginal value of the private output x_i decreases as more of the public output Z is produced), then $\frac{\partial MRS^i_{xy}}{\partial Z}$ is negative. In this case, the substitutability and the diminishing marginal rate of substitution effects reinforce each other and *sign* $\left[\frac{\partial n_i}{\partial n_j}\right]$ is negative and ally i decreases its contribution of defence input n_i in response to an increase in ally j's contribution n_j.

We now determine *sign* $\left[\frac{\partial m_i}{\partial n_j}\right]$. Implicit differentiation of (15) with respect to n_j gives

$$\frac{dm_i}{dn_j} = \frac{\partial m_i}{\partial n_i}\frac{\partial n_i}{\partial n_j} + \frac{\partial m_i}{\partial n_j} = \frac{g_i{}'}{h_i{}'}\frac{\partial n_i}{\partial n_j} + \frac{g_j{}'}{h_i{}'},$$

which, given (25) and (26), implies

$$\frac{dm_i}{dn_j}\begin{cases} \geq 0 \text{ if} \begin{cases} \frac{\partial n_i}{\partial n_j} \geq 0 \text{or} \\ \frac{\partial n_i}{\partial n_j} \leq 0 \text{and} \frac{\partial n_i}{\partial n_j} \geq -\frac{g_j^{'}}{g_i^{'}} \end{cases} \\ \leq 0 \text{if} \quad \frac{\partial n_i}{\partial n_j} \leq 0 \text{and} \frac{\partial n_i}{\partial n_j} \leq -\frac{g_j^{'}}{g_i^{'}}. \end{cases} \tag{27}$$

Equation 27—reveal a few interesting properties. First, if ally i increases its contribution of technology as a response in an increase in ally j's contribution of techonogy, then it will also increase its contribution of land; that is, if $\frac{\partial n_i}{\partial n_j} \geq 0$, then $\frac{dm_i}{dn_j} \geq 0$. Interestingly, ally i may still increase its contribution of land in response to an increase in ally j's contribution of technology, while decreasing its contribution of technology; that is, $\frac{dm_i}{dn_j} \geq 0$ even if $\frac{\partial n_i}{\partial n_j} \leq 0$. This is the case when ally i's technology is less productive in producing the public output compared with ally j's technology; that is, $\frac{g_j^{'}}{g_i^{'}}$ is relatively high.[10] This result is new and shows that an ally may respond to an increase in other allies' contributions of technology by contributing more land and less technology, if that ally's technology is less productive in producing the public output compared with other allies. This effect is shut down in the standard joint products model, in which there is only one defence input – military expenditures – producing a private and public output, and, thus, an ally can respond to an increase in other allies' contributions of this input either by increasing or decreasing its own contributions. Here, we show that an ally can respond by increasing its contributions of some inputs (land m_i), while decreasing its contribution of other inputs (technology n_i).

The last inequality in Equaiton 27 shows that if ally i's technology is more productive in producing the public good compared with ally j's technology, then ally i responds to an increase in ally j's contribution of technology by decreasing its contribution of both inputs – technology and land.

Next, we determine *sign* $\left[\frac{\partial n_i}{\partial m_j}\right]$, by implicit differentiation of (22) with respect to m_j

$$\Phi\frac{\partial n_i}{\partial m_j} = -p_M\frac{g_i^{'}h_{ij}^{''}}{(h_i^{'})^2}. \tag{28}$$

Thus,

$$\frac{\partial n_i}{\partial m_j}\begin{cases} \geq 0 \text{if} h''_{ij} \geq 0, \\ \geq 0 \text{if} h''_{ij} \leq 0. \end{cases} \tag{29}$$

Equation 29 shows that a change in ally j's contribution of land has only second-order effects on ally i contribution of technology. If these effects are small or zero ($h_{ij}^{''} = 0$), then an increase in ally j's contribution of land has no effect on ally i contribution of technology. The second-order effects, $h_{ij}^{''}$, give a measure of the effect of ally j's contribution of land on the marginal product of ally i's contribution of land; an increase in ally j's land contribution may increase ($h_{ij}^{''}>0$) or decrease ($h_{ij}^{''}<0$)

the marginal product of ally i's land contribution. Assuming that the total land input, M, is produced with a fixed amount physical capital, we expect that, in general, the second-order effects to be negative, albeit small. This means that there are diminishing returns to land contributions of both allies. In the next section, we analyze the case when land contributions are imperfect substitutes, in which case, the second-order effects are zero.

Last, we determine $\frac{\partial m_i}{\partial m_j}$, by implicit differentiation of (15) with respect to m_j

$$\frac{dm_i}{dm_j} = \frac{\partial m_i}{\partial n_i}\frac{\partial n_i}{\partial m_j} + \frac{\partial m_i}{\partial m_j} = \frac{g_i^{'}}{h_i^{'}}\frac{\partial n_i}{\partial m_j} - \frac{h_j^{'}}{h_i^{'}}. \tag{30}$$

Thus,

$$\frac{dm_i}{dm_j}\begin{cases} \geq 0 \text{ if } \frac{\partial n_i}{\partial m_j} \geq \frac{h_j^{'}}{g_i^{'}}, \\ \leq 0 \text{ if } \frac{\partial n_i}{\partial m_j} \leq \frac{h_j^{'}}{g_i^{'}}. \end{cases} \tag{31}$$

Equation 31 shows that if ally i has a comparative advantage in producing technology, that is, $\frac{h_j^{'}}{g_i^{'}}$ is relatively small, then ally i responds to an increase in ally j's contribution of land by increasing its own contribution of both land and technology if $h_{ij}^{''} \geq 0$; that is, $\frac{dm_i}{dm_j} \geq 0$ and $\frac{\partial n_i}{\partial m_j} \geq 0$. If, on the other hand, ally j has a comparative advantage in producing land $\frac{h_j^{'}}{g_i^{'}}$ is relatively high, then ally i responds to an increase in ally j's contribution of land by decreasing its own contribution of both land and technology if $h_{ij}^{''} \leq 0$. If the second-order effects $h_{ij}^{''}$ are zero, then (30)—(31) indicate that ally i responds to an increase in ally j's contribution of land by decreasing its own contribution of land and keeping its contribution of technology constant.

Imperfect Substitute Inputs

In this section, we assume that the defence inputs, n_i and n_j, and m_i and m_j, are imperfect substitutes, respectively, and the country-specific private output, x_i, is produced with a fixed-proportions techonology. These are standard assumptions in the joint-products model and allow us to directly compare the predictions of our model with those of the joint-products model. Thus,

$$N = g(n_i, n_j) = \beta_i n_i + \beta_j n_j \tag{32}$$

$$M = h(m_i, m_j) = \gamma_i m_i + \gamma_j m_j \tag{33}$$

and

$$x_i = f_i(n_i) = \alpha_i n_i \tag{34}$$

with $\alpha_i > 0$, $\beta_i > 0$, and $\gamma_i > 0$, for $i \in \{A, B\}$. The Leontief technology then implies

$$Z = F(N, M) = \min\{\beta_i n_i + \beta_j n_j, \gamma_i m_i + \gamma_j m_j\} \tag{35}$$

With these functional forms, the comparative statics properties derived above become:

$$\frac{\partial n_i}{\partial n_j}\left\{ \geq 0 \text{ if } f_i^{'}\frac{\partial MRS_{xy}^i}{\partial Z} + g_i^{'}\frac{\partial MRS_{Zy}^i}{\partial Z} \geq 0 \right. \tag{36}$$

$$\frac{\partial n_i}{\partial n_j}\left\{ \leq 0 \text{if } f_i^{'}\frac{\partial MRS_{xy}^i}{\partial Z} + g_i^{'}\frac{\partial MRS_{Zy}^i}{\partial Z} \leq 0 \right. \tag{37}$$

Table 1. Comparative Statics Properties when Inputs are Imperfect Substitutes.

Conditions		$\frac{\partial n_i}{\partial n_j}$	$\frac{\partial m_i}{\partial n_j}$	$\frac{\partial n_i}{\partial m_j}$	$\frac{\partial m_i}{\partial m_j}$
$f_i' \frac{\partial MRS^i_{xy}}{\partial Z} + g_i' \frac{\partial MRS^i_{Zy}}{\partial Z} \geq 0$		+	+	0	-
$f_i' \frac{\partial MRS^i_{xy}}{\partial Z} + g_i' \frac{\partial MRS^i_{Zy}}{\partial Z} \leq 0$	$\frac{\beta_j}{\beta_i}$ large	-	+	0	-
	$\frac{\beta_j}{\beta_i}$ small	-	-	0	-

$$\frac{\mathrm{d}m_i}{\mathrm{d}m_j} < 0 \tag{38}$$

$$\frac{dm_i}{dn_j}\left\{ \geq 0 \text{ if} \left\{ \frac{\partial n_i}{\partial n_j} \geq 0 \right.\right. \tag{39}$$

or

$$\frac{dm_i}{dn_j}\left\{ \geq 0 \text{ if} \left\{ \frac{\partial n_i}{\partial n_j} \leq 0 \text{ and} \frac{\partial n_i}{\partial n_j} \geq -\frac{\beta_j}{\beta_i} \right.\right. \tag{40}$$

$$\frac{dm_i}{dn_j}\left\{ \leq 0 \text{ if} \frac{\partial n_i}{\partial n_j} \leq 0 \text{ and} \frac{\partial n_i}{\partial n_j} \leq -\frac{\beta_j}{\beta_i} \right. \tag{41}$$

$$\frac{\partial n_i}{\partial m_j} = 0 \tag{42}$$

Table 1 summarizes these comparative statics properties.

In order to interpret the results given in Equation 36—Equation 41, it is important to understand the difference between the two types of defence inputs, n_i vs m_i. Defence input $M = \gamma_i m_i + \gamma_j m_j$ is a pure public input, which in our case could represent land or another military domain. Given that the defence inputs provided by the two allies are imperfect substitutes, each ally will respond to an increase in the public defence input by the other ally, by reducing its own contribution. As expected, this gives rise to free-riding in the contributions to the pure public input M. This is reflected by the negatively-sloped reaction function $\frac{\mathrm{d}m_i}{\mathrm{d}m_j} < 0$.

Defence input $N = \beta_i n_i + \beta_j n_j$, on the other hand, is an impure public input that generates both alliance-wide public benefits, Z, and country-specific private benefits, x_i. This is exactly the case of the joint-products model. An ally's response to an increase in the other's contribution of techonology depends on whether the public defence output, Z, and the private output, x_i, are substitutes or complements in the Hicksian sense, and, in the latter case, on which of the diminishing marginal rate of substitution or the complementarity effect dominates.

It is clear at this point that our model combines the features of both the public goods and the joint products models. If defence input n_i does not have a private benefit, then the model collapses to the public goods model; if the public defence output, Z, is produced only with defence input n_i, the model collapses to the joint products model.

Equation 38—Equation 41 show the effects of considering both defence inputs on allies' contributions. Equation 38 shows that ally i may respond to an increase in ally j's contribution of technology by increasing its own contribution of both technology and land; this is the case if the public output, Z, and the private output, x_i, are complements in the Hicksian sense and the complementarity effect dominates the diminishing marginal rate of substitution effect. If that is not the case, that is, either the the public output, Z, and the private output, x_i, are substitutes in the Hicksian sense or the diminishing marginal rate of substitution effect dominates, then ally i's response to an increase in ally j's contribution of technology is to decrease its own contribution of technology. Whether or not ally i increases or decreases its contribution of land at the same time, depends on allies' relative productivity of technology in producing the public good. If ally i's technology is relatively less productive (β_i is small compared with β_j), then ally i responds to an increase in ally j's increase in technology contribution by increasing its contribution of land to make up for the decrease in its contribution of technology; this is shown by Equation 39. If, on the other hand, ally i's technology is relatively more productive (β_i is large compared with β_j), then ally i responds by decreasing its contribution of land and technology; this is shown by (44).

Interestingly, a change in ally j's land contribution has no effect on ally i technology contribution; this is shown by (45). Recall from (31) and (32) that effect of a change in ally j's contribution of land on ally i contribution of technology depends on the second-order effect h''_{ij}, which is now zero given that allies' land contribution are imperfect substitutes. The intuition for this result is simple. Ally i responds to an increase in ally j's land contribution by decreasing its own land contribution, such that the total land contribution, M, is unchanged.[11] Given that technology and land are complement inputs in the production of the public defence input, Z, this implies that total technology contribution does not change either as a result of an increase in ally j's contribution of land, ceteris paribus. Thus, ally i's technology contribution does not change.

Conclusions

In most, if not all, military alliances, the alliance-wide defence output is produced with multiple defence inputs. Distinguishing different defence inputs is particularly appropriate in the case of NORAD, as the alliance-wide defence output is produced with two inputs – military technology in the form of sensors and radars and land. These two inputs are complements in the production of the alliance-wide public output. At the same time, the military technology has country-specific private benefits as this can be used by the civilian economy. One output of the Modernized NORAD is 'early detection of missiles', reducing the likelihood of false negatives from the current NORAD radar system and that is the public good. However, the Modernized NORAD, if designed so, can generate a Northern telecommunications network built on multi-mission sensors thus the private Northern benefits. It may also trigger positive externalities in the form of development along the infrastructure sustaining the new and modernized radar stations.

Our model extends the joint-products models to allow for two types of defence inputs used to produce both an alliance-wide public defence output and a country-specific private output. Our analysis shows that distinguishing between defence inputs may change the predictions of the joint-products model. We derive conditions under which an ally responds to an increase in the defence input by other allies by increasing or decreasing its own contribution of both or only one of the defence inputs. In particular, we show that an ally, whose technology is less productive in producing the public defence output than the other ally, responds to an increase in the technology contribution of the other ally by decreasing its own contribution of technology and increasing its contribution of land. That same ally responds to an increase in the land contribution of the other ally by decreasing its own contribution of land. If, however, an ally's technology is more productive in producing the public defence output than the other ally, that ally responds to an increase in the technology contribution of the other ally by increasing its own contributions of both defence inputs – technology and land. That same ally responds to an increase in the land contribution of the other ally by increasing its own contribution of land. An increase in an ally's contribution of land may result in an increase, decrease, on no change in the other ally's contribution of technology, depending on the strength of the second-order effects. These results show that the joint-products model with one defence input – military expenditures – does not offer a full picture of allies' responses to other allies changes in defence input contributions. Our model combines features of both the public goods and the joint-products models and, thus, offers a more nuanced analysis of allies' incentives and behaviour in a military alliance.

Whereas the empirical validation of our theoretical model remains an area for future research, one potential extension could be to modify and extend the game to the post-Modernization period where an adversarial game is considered. The defensive early-warning system has to upgrade the network in anticipation of faster and random approaches by cruise missiles and hypersonic gliding vehicles. A differential game, stochastic or not, perhaps similar to a patent race, might be an option. A stochastic game seems promising as building this capability should be considered a one-shot investment with continuous tweaks geared to sensors and other components, both in the sense of hardware and software. Since the modernized early warning system has to be designed to be modular to allow for plug-and-play upgrades, we think there would be little gain in that extension direction. Moreover, although uncertainty over adversarial behaviour (re: a belligerent Russia under Putin) is endemic, in the game between these two allies there seems to be no significant uncertainty on the alliance in the post-Trump era, except the regular nudges regarding burden-sharing.

Notes

1. The empirical literature on burden-sharing in the NATO alliance before 1967 uses defence expenditure as a percentage of GDP as a measure of burden sharing and finds evidence for the 'exploitation' of the large and rich allies by small and poor allies (Khanna and Sandler 1996). However, Bogers and Beeres (2013) use indicators such as deployability ands sustainability and find that the ranking of the burden-sharing in NATO depends critically on the specific measure of burden sharing. Beeres and Bollen (2017), Beeres and Bogers (2012), and Kollias (2008) study the burden-sharing problem at the level of the European Union and provide further evidence that the burden-sharing ranking changes depending on the specific measure employed.
2. Sandler and Hartley (2001) is an excellent review of the joint-products model literature.
3. NATO member states to spend 2% of their GDPs in defence and 20% of that on equipment.
4. Canadian land contribution allows resiliency as, instead of relying solely on LEO-orbit satellites, drones and fixed-wing patrol aircraft, by permitting over-the horizon radar stations on land (with Modernized NORAD reaching up to 2,000 km further north) and underwater sensors, effectiveness increases through redundancy and diversification.
5. For a discussion of the Northwest Passage sovereignty dispute see (Elliott-Meisel 2009), and (Lajeunesse and Huebert 2019).
6. In section 2.3 we present the case when defence inputs are imperfect substitutes. Our model is, however, general enough to allow for the case of a weakest-link input aggregation technology. If either ally withdraws its contribution of land (or technology), the alliance-wide defence is produced with the minimum contribution of land and technology. Thus, the model allows either of both weakest link and weaker link technologies. 'In contrast to the weakest-link technology, if one agent is not contributing it is still possible to attain positive levels of the public good.' (Arce 2001). So it was weaker link but that does not change this paper's results, it just requires a recalibration of payoffs to the alliance production function by lifting the public good from zero to some positive threshold.
7. As for the land prices up North, whereas the land use is at a excess supply equilibrium even at zero price for local and civilian uses in those remote areas where NORAD radar stations are installed, there is an imputed price which derives from the benefits generated by NORAD.
8. Our model, as well as the related standard joint-products model, can be contrasted with the alternative under which the members of the military alliance would be sharing the total cost of providing the efficient level of defence for the alliance.
9. Note that, if both inputs contribute to the production of both the country-specific output and the alliance-wide output, the model collapses to the standard joint-products model and the distinction between the two inputs becomes irrelevant.
10. If $\frac{\partial n_i}{\partial n_j} \leq 0$, the condition in (27), becomes $\left|\frac{\partial n_i}{\partial n_j}\right| \leq \frac{g'_j}{g'_i}$.
11. Differentiating the aggregation technology for land, $M = \gamma_i m_i + \gamma_j m_j$ with respect to m_j, gives.

    $\frac{\partial M}{\partial m_j} = \gamma_i \frac{\partial m_i}{\partial m_j} + \gamma_j$.

    Substituting in $\frac{\partial m_i}{\partial m_j} = -\frac{\gamma_j}{\gamma_i}$ from (34) or (35) for $h''_{ij} = 0$, gives $\frac{\partial M}{\partial m_j} = 0$.

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References

Arce, D. 2001. “Leadership and the Aggregation of International Collective Action.” *Oxford Economic Papers* 53 (1): 114–137. doi:10.1093/oep/53.1.114.

Beeres, R., and M. Bogers. 2012. “Ranking the Performance of European Armed Forces.” *Defence and Peace Economics* 23 (1): 1–16. doi:10.1080/10242694.2011.578401.

Beeres, R., and M. Bollen. 2017. “Towards a European Defence Union? Military Burden Sharing in the European Union 2006-2013.” *Athens Journal of Social Sciences* 4 (2): 147–160. doi:10.30958/ajss.4-2-3.

Berkok, U., O. Secrieru, K. Peyrow Lee, and K. Kodis. 2022. “North American Aerospace Defence (NORAD) Modernization: Challenges and Opportunities.” Defence Research & Development Canada Report DRDC-RDDC-2022-C144.

Bogers, M., and R. Beeres. 2013. “Mission Afghanistan: Who Bears the Heaviest Burden.” *Peace Economics Peace Science and Public Policy* 19 (1): 32–55. doi:10.1515/peps-2013-0002.

Brockmann, K., and M. Schiller. 2022. “A Matter of Speed? Understanding Hypersonic Missile Systems.” https://www.sipri.org/commentary/topical-backgrounder/2022/matter-speed-understanding-hypersonic-missile-systems?utm_source=phpList&utm_medium=email&utm_campaign=SIPRI+Update+February+2022%3A+SIPRI+at+MSC%2C+hypersonic+missile+systems%2C+avoiding+nuclear+war%2C+the+Anthropocene+and+more&utm_content=HTML (Accessed 23 February 2022).

Brown, J. M. 2014. “Strategy for Intelligence, Surveillance, and Reconnaissance.” *Joint Force Quarterly* 72: 39–46.

Charron, A., and J. Fergusson. 2020. “Out of Sight, Out of Mind NORAD Vis-à-Vis CANUS Politics.” *Canadian Foreign Policy Journal* 26 (2): 137–151. doi:10.1080/11926422.2019.1670221.

Charron, A., J. Fergusson, J. Jockel, C. Sands, and J. Sokolsky. 2019. “NORAD: Beyond Modernization.” In *Centre for Defence and Security Studies*. [(accessed 23 February 2022]. University of Manitoba. https://umanitoba.ca/centres/cdss/papers/2201.html

Congressional Research Service (CRS). 2022. “Joint All-Domain Command and Control (JADC2).” (Accessed 24 March 2022).

Conybeare, J. A. C., J. C. Murdoch, and T. Sandler. 1994. “Alternative Collective Goods Models of Military Alliances: Theory and Empirics.” *Economic Inquiry* 32 (4): 525–542. doi:10.1111/j.1465-7295.1994.tb01349.x.

Corbett, M. 2013. “A New Approach to Ballistic Missile Defense for Countering Antiaccess/area-Denial Threats from Precision-Guided Weapons.” *Air & Space Power Journal* 27 (3): 83–106.

Cornes, R. 1993. “Dyke Maintenance and Other Stories: Some Neglected Types of Public Goods.” *The Quarterly Journal of Economics* 108 (1): 259–271. doi:10.2307/2118503.

Cornes, R., and T. Sandler. 1984. “Easy Riders, Joint Production, and Public Goods.” *The Economic Journal* 94 (375): 580–598. doi:10.2307/2232704.

Cornes, R., and T. Sandler. 1994. “The Comparative Static Properties of the Impure Public Good Model.” *Journal of Public Economics* 54 (3): 403–421. doi:10.1016/0047-2727(94)90043-4.

Csenkey, K., and D. P. Genest. 2021. “An Opportunity for NORAD Modernization in a Joint CA-US Cyber Component.” Strategic Perspectives, North American and Arctic Defence and Security Network, (Accessed 21 March 2022).

Droff, J., and J. Malizard. 2020. “Menaces, biens publics et demande de défense européenne.” *Revue Défense Nationale* N° 828 (3): 95–100. doi:10.3917/rdna.828.0095.

Elliott-Meisel, E. 2009. “Politics, Pride, and Precedent: The United States and Canada in the Northwest Passage.” *Ocean Development & International Law* 40 (2): 204–232. doi:10.1080/00908320902864813.

Fergusson, J. 2020. *“Missed Opportunities: Why Canada’s North Warning System is Overdue for an Overhaul”*. Commentary: Macdonald-Laurier Institute.

Fetterly, R., and B. Solomon. 2021. “North American Aerospace Defense Command (NORAD) Burden Sharing.” https://cradpdf.drdc-rddc.gc.ca (Accessed 26 march 2022).

Jenkins, T. 2013. “Canada First: Leveraging Defence Procurement Through Key Industrial Capabilities.” https://www.ic.gc.ca/eic/site/086.nsf/eng/h_00175.html (Accessed 27 march 2022).

Khanna, J., and T. Sandler. 1996. “Nato Burden Sharing: 1960–1992.” *Defence and Peace Economics* 7 (2): 115–133. doi:10.1080/10430719608404846.

Kieley, M. 2021. “No Umbrella for the Rain: Canadian Implications Following the Global Revolution in Reconnaissance–Strike Technologies.” *International Journal: Canada’s Journal of Global Policy Analysis* 76 (2): 221–237. doi:10.1177/00207020211019301.

Kollias, C. 2008. “A Preliminary Investigation of the Burden Sharing Aspects of a European Union Common Defence Policy.” *Defence and Peace Economics* 19 (4): 253–263. doi:10.1080/10242690802164777.

Lajeunesse, A., and R. Huebert. 2019. “Preparing for the Next Arctic Sovereignty Crisis: The Northwest Passage in the Age of Donald Trump.” *International Journal: Canada’s Journal of Global Policy Analysis* 74 (2): 225–239. doi:10.1177/0020702019849641.

Lamont, L., Déziel, M., and Patterson, G. 2011. “Tiered Wireless Sensor Network Architecture for Military Surveillance Applications.” *SENSORCOMM 2011 : The Fifth International Conference on Sensor Technologies and Applications, Proceedings*, https://www.researchgate.net/publication/268350779_Tiered_Wireless_Sensor_Network_Architecture_for_Military_Surveillance_Applications (accessed 23 March 2022).

Mallory, K. 2018. “New Challenges in Cross-Domain Deterrence.” RAND Corporation, https://www.rand.org/search.html?query=New+Challenges+in+Cross-Domain+Deterrence (Accessed 21 February 2022).

Murdoch, J. C., and T. Sandler. 1982. “A Theoretical and Empirical Analysis of NATO.” *The Journal of Conflict Resolution* 26 (2): 237–263. doi:10.1177/0022002782026002003.

Murdoch, J. C., and T. Sandler. 1984. “Complementarity, Free Riding, and the Military Expenditures of NATO Allies.” *Journal of Public Economics* 25 (1–2): 83–101. doi:10.1016/0047-2727(84)90045-8.

Olson, M., and R. Zeckhauser. 1966. “An Economic Theory of Alliances.” *The Review of Economics and Statistics* 48 (3): 266–278. doi:10.2307/1927082.

RADA. 2020. “Tactical Multi-Mission Sensors in the Defense Environment.” https://radausa.com/blog/multi-mission-sensors (Accessed 21 March 2022).

Sandler, T. 1977. “Impurity of Defense: An Application to the Economics of Alliances.” *Kyklos* 30 (3): 443–460. doi:10.1111/j.1467-6435.1977.tb02203.x.

Sandler, T., and J. Forbes. 1980. “Burden Sharing, Strategy, and the Design of NATO.” *Economic Inquiry* 18 (3): 425–444. doi:10.1111/j.1465-7295.1980.tb00588.x.

Sandler, T., and K. Hartley. 1995. *The Economics of Defense*. Cambridge: Cambridge University Press.

Sandler, T., and K. Hartley. 2001. “Economics of Alliances: The Lessons for Collective Action.” *Journal of Economic Literature* 39 (3): 869–896. doi:10.1257/jel.39.3.869.

Sherman, J. 2021. “Forging a SHIELD for the Homeland.” https://www.airforcemag.com/article/forging-a-shield-for-the-homeland/ (Accessed 26 March 2022).

van Ypersele de Strihou, J. 1967. “Sharing the Defense Burden Among Western Allies.” *The Review of Economics and Statistics* 49 (4): 527–536. doi:10.2307/1928338.

Verklan, C. 2021. “NORAD Modernization: Considering the Threat of Small UAS to (Integrated) Air and Missile Defence.” Policy Primer, North American and Arctic Defence and Security Network, (Accessed 31 January 2022).