THREE ESSAYS ON ENVIRONMENTAL ECONOMICS AND

CLIMATE CHANGE POLICY

by

BEOMSEOK YOON

(Under the Direction of Mateusz Filipski and Craig Landry)

ABSTRACT

This dissertation is a collection of three studies that identify unintended behaviors of economic agents in environmental economics, centered on the climate change policies, investigate the causes of such behaviors, and try to find the alternatives to minimize the resulting effects. The first essay explains agents' trading behaviors and markets in the presence of endowment effects in carbon cap and trade, building on the reference-dependent model of Kőszegi and Rabin (2006) with forward-looking reference points. This study supports the notion that auction allocation of allowances can be socially preferable to free allocation and explores policy options that can mitigate unintended results caused by endowment effects and that enable ambitious climate actions under the Paris Agreement.

The second essay studies the carbon price movements under the expectation for insufficient market supply in the Korean Emission Trading Scheme (K-ETS). We theoretically overview that the expectation for insufficient market supply can significantly increase current allowance prices by intertemporal no-arbitrage. We empirically investigate allowance price movements, comparing them to a random walk process under the weak-form market efficiency (Fama, 1965) as a reference.

We present that uncertain price rules under the shortage of market supply can cause higher variations of firms' expectations, which can be made worse by a short-term cap (uncertain long-term policy) and a high proportion of free allocations (firms' uncertain holding tendency). We explore policy options that can be harmonized with individually constrained banking, the current main intervention in the K-ETS.

The third essay investigates how the main variables in the agricultural production economy respond to weather shocks, constructing an estimated dynamic stochastic general equilibrium (DSGE) model with multi-sectors on the U.S. data. We find that with the shock in weather-driven losses the contribution of weather shocks can be significant for fluctuations of the main variables (output, capital, investment, and land costs) even in the short term. We show that the technological progress (possibly through the public R&D) and the adjustment of agricultural lending rates (possibly linked to incentives for sustainable practices) can lead to a more rapid recovery of output losses caused by extreme weather events.

INDEX WORDS: Banking Tendency, Cap and Trade, Carbon Price, Endowment Effect, Expectation, Weather Shocks, DSGE, Agricultural Production, Drought

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DEDICATION

This dissertation is dedicated to my Lord, Jesus Christ, who came to me, showed me this way, led me at every step, and is still with me.

I would like to thank my family for their unconditional love and support. I would also like to express my deep gratitude to Senior Pastor YS Baek, mentor Pastor OW Kwon, and local church Pastor CK Kim for guiding my life in his way.

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CHAPTER 1

ENDOWMENT EFFECTS, EXPECTATIONS, AND TRADING BEHAVIOR IN CARBON CAP AND TRADE

1.1. INTRODUCTION

The cap-and-trade system is based on the idea that market equilibrium will be cost-effective.[1] That is, the overall cost of achieving an emission reduction goal will be minimized by a well-functioning market for allowances (carbon permits), because prices will incentivize firms with low abatement cost to reduce emissions and firms with high abatement cost to buy allowances from the market. Hence, cap and trade systems have been promoted as a policy instrument to control pollutants and are becoming one of the major options for the implementation of nationally determined contributions (NDC) under the Paris Agreement.

The prerequisite of this cost-effectiveness in the allowance market is the mutually beneficial trading among players, and the consequent "independence property", by which the final allocation of emission allowances is independent of their initial allocation (Hahn and Stavins, 2011). This assumption has been subject to debate. Some studies support the "independence property" in cap-and-trade systems (Reguant and Ellerman, 2008; Fowlie and Perloff, 2013), while Murphy and Stranlund (2007) find that net sellers tend not to sell their allowances in expected quantities and show lower compliance violation levels than net buyers. Such findings, along with market frictions observed in carbon markets, motivate this study.

Market liquidity problems have been raised around several cap-and-trade systems for the implementation of the Paris Agreement (Asian Development Bank, 2016; 2018). Low volumes of allowances were traded with high price volatilities in the Chinese Emission Trading Scheme (ETS) pilot, presumably due to the small size of the market, insufficient demand, lack of public information on supply and demand of allowances, and unfamiliarity of participants with market operations (Asian Development

[1] Cost-effectiveness means to achieve an overall emissions target at the lowest cost.

Bank, 2016; Zhao et al., 2016). For the Korean ETS, Suk et al. (2018) argue that the key barriers to active trading are supply-demand imbalances (high demand), policy uncertainty, and a lack of preparedness of firms. The Asian Development Bank (2018) suggests that Korea's unlimited banking rule may have caused firms to bank most of their surplus allowances for fear of higher prices in the following year.

We focus on agents' preferences and their trading behavioral properties. Based on Expected Utility Theory, there are a few studies that indicate that trade in allowances can be limited (or banking can be preferred) by uncertainty and risk-aversion (Ben-David et al., 2000; Baldursson et al., 2004; Rousse O. et al., 2007). However, these studies cannot fully explain loss avoiding behaviors caused by concerns about financial losses in risk-neutral firms, tendencies to wait and see the market (Engels et al., 2008; Suk et al., 2018), or the gap between Willingness-To-Pay (WTP) and Willingness-To-Accept (WTA) frequently found in other goods or commodities. Baudry et al. (2021) also indicate that with behavioral biases firms may recognize allowances as an instrument for compliance rather than that for profits from allowance trading.

Hahn and Stavins (2011) present that in cap and trade the "independence property" can break down in the presence of endowment effects. There are several studies exploring the reason for endowment effects such as transaction costs (Stavins, 1995), market power (Hahn, 1984), and fewer experiences (Plott, 1996). However, we aim to fill the above gaps in Expected Utility Theory, using one formulation of Kahneman and Tversky's prospect theory (1979). This theory posits that initial endowments create reference points (reference dependence), and losses are regarded more valuable than equivalent gains (loss aversion), causing an endowment effect.[2] In cap and trade, such endowment effects may be shown by the gap between

[2] Many studies find evidence consistent with prospect theory in finance, insurance, and consumption-saving decisions (Barberis, 2013), and empirical evidence on loss aversion is generally abundant (e.g., Horowitz and McConnell, 2002; Xie et al., 2018; Heutel, 2019). Pollitt et al. (2013) also argue that prospect theory can be applied to energy and climate policy.

WTP and WTA for allowances, and by sellers' strong tendencies to bank their allowances.[3] Our work is among the first to shed light on these mechanisms.[4]

The purpose of our paper is to show how fewer transactions may be explained by endowment effects and what systemically causes these endowment effects in allowance trading. Building on reference-dependent preferences by prospect theory, we specifically seek to answer the following questions: i) how do those preferences influence agents' trading behavior in cap and trade; ii) What effect do those have on the current market equilibrium; and iii) how can unintended effects be reduced?

While most studies on reference-dependent preferences consider backward-looking reference points (e.g., Simonsohn and Loewenstein, 2006; DellaVigna, 2017) or status quo (e.g., Abeler et al., 2011), we use agents' rational expectations as forward-looking reference points based on Kőszegi and Rabin (2006). A forward-looking approach is more reasonable for cap and trade, especially when firms risk financial losses in the case of a shortage of allowances, market participants are primarily firms sensitive to compliance failure, and market liquidity problems are expected under a high proportion of free allocation. Cap and trade systems are not unfamiliar with the forward-looking approach. In our paper, this approach is linked to implications that expectations matter in the formulation of carbon prices, based on intertemporal no arbitrage conditions in the recent literature (Borenstein et. al. 2019; Aldy and Armitage, 2020; Pizer and Prest, 2020).

We use two frameworks of analysis, at the agent and at the market level. First, we adapt the Kőszegi and Rabin (2006) behavioral model to the case of a firm trading allowances in a cap-and-trade system. We show that an agent's behavior will depend on whether insufficient market supply (specifically, the shortage of allowances in the market) is expected in the next period. In the event of a supply shortage under a fixed cap, allowance prices would be subject to upside risk (Halt and Shobe, 2016; Salant, 2016; Fell, 2015), and

[3] The term "bank" is generally used for the administrative action at the end of each compliance cycle, while the term "hold" is used for the action at any given time. However, this study does not differentiate between those meanings.

[4] An exception is Song and Ahan (2019) who empirically show a gap between WTP and WTA in sellers. However, they identify the gap just in simple contingent situations, and did not explain why and how the endowment effect occurs.

lead to exceedingly high compliance costs for firms. We also show that in forward-looking approach, the variability of reference points can significantly influence the agent's utility and her marginal WTA/P (MWTA/MWTP). Our results are illustrated with numerical simulations using the "relative MWTA index" introduced in this study.

Second, at the market level, we apply a general conceptual framework with supply/demand curves for allowances, building on the recent literature that market price in a dynamic setting with unlimited banking are significantly affected by participants' expectations with the intertemporal no arbitrage condition.[5] This approach can better capture the change in market equilibrium as agents' behaviors in the market change, compared to the efficiency framework and the cost-effectiveness framework generally analyzed for cap and trade systems. Our analysis shows that the gap between MWTA for sellers and MWTP for buyers can cause the decrease in equilibrium supply/demand and that even when the market exhibits allowance surpluses in the current period, allowance prices can significantly increase with agents' expectations of future supply shortages and higher variances of expected allowance prices.

We further investigate potential circumstances in the real world which may lead to expectations of insufficient supply, including higher supply variance. They include the atmosphere of the Paris Agreement which stimulates ambitious actions, and various uncertainties from each factor of market supply like the cap and the market emission. In the context of the Paris Agreement, our investigations are valuable because cap and trade systems should also deal with agents' expectations for continuously decreasing caps and uncertainties around supply and consequent price. The case of the Korea Emission Trading Scheme (K-ETS) under a short-term fixed cap and high proportion of free allocation, which experiences high banking demands under the expectation of insufficient market supply, is also introduced as an empirical illustration.

Finally, we explore policy alternatives to meet long-term climate goals. Our study supports the notion that auction allocation can be socially preferable to free allocation in that buyers in the auction are free from sellers' MWTA. Specifically, under high proportion of free allocation and expectations of insufficient

[5] Lintunen and Kuusela (2018); Kuusela and Lintunen (2019); Borenstein et al., 2019; Aldy & Armitage, 2020; Pizer & Prest (2020); Quemin and Trotignon (2021)

market supply for the future, sellers' high MWTA can lead to high willingness-to-bank, supply shortage, and unintended price hikes at the current period. Next, temporary additional allocations in the case of a shortage (perhaps arising from uncertain national GHG target under the Paris Agreement) would not be helpful because it barely affects sellers' reference prices under continuous concerns about supply shortage. We explore policy options such as i) the long-term cap harmonized with a safety valve that can control sellers' MWTA and price-inelastic compliance demands within a price ceiling (under a short-term cap, it is almost impossible to even form the expected price in the future), and ii) measures to avoid excessive banking (or market power).

In section 1.2 we introduce our reference-dependence model, investigate the agent's behaviors based on this model and check those through numerical simulations. Section 1.3 presents the effects of these behaviors on the allowance market in terms of the trading volume and price and investigates potential cases in the real world which may cause the expectation of insufficient market supply and higher supply variations. Section 1.4 investigates potential options to prevent or correct the problems caused by endowment effects, and section 1.5 summarizes and concludes.

1.2. The Trading Behavior of Each Agent

1.2.1. The theoretical model and its properties

This paper starts from Kőszegi and Rabin's model (2006, 2007) where an agent's preferences are reference-dependent and loss-averse. This model has been used to explain endowment effects, disparities between WTP and WTA, and behavioral characteristics in various areas including consumption or savings (Keith et. al., 2011; Barber, 2016; Diez and Venmans, 2019), insurance (Viscusi and Huber, 2012; Koetse and Brouwer, 2016), and job search (DellaVigan et. al., 2017). In this model, the agent's utility depends not just on the level of consumption of W but also on the difference (X) between the level of the payoff (W) and a reference level (r) ($X = W - r$):

$$U(W) = \underbrace{w(W)}_{\substack{payoff-level \\ utility}} + \eta \cdot \underbrace{\int \mu(X \mid r) dF(r)}_{\substack{gain-loss \\ utility}}, \tag{1.1}$$

where $\eta \geq 0$ represents the relative weight of gain-loss utility (reference dependence) and $F(r)$ as the cumulative distribution function (*c.d.f.*) of a reference point r.[6]

In the context of cap and trade, firms try to maximize their payoffs through abatement investments and trading for allowanced generated by abatement efforts. If the agent has reference-dependent preferences, the sensitivity to gains and losses from a reference level significantly affects her utility. In our model, the reference point is forward-looking, endogenously determined by expectations of future allowance prices as in Kőszegi and Rabin's model (2006, 2007). Therefore, the reference point is a random variable with a probability distribution function (*p.d.f.*) of given mean and variance. For simplicity, we assume that the payoff-level utility is linear ($w(W) = W$). As for a gain-loss utility, we apply the functional form proposed by Tversky and Kahneman (1992), given a reference point.

$$\mu(X \mid r) = \begin{pmatrix} u(X^+) & if\ X > 0 \\ -\lambda \cdot u(-X^-) & if\ X < 0 \end{pmatrix}, \tag{1.2}$$

where X^+ if $X > 0$ and X^- if $X < 0$. Here λ represents the parameter of loss aversion for each agent, and we assume that $u(\cdot)$ is increasing ($u'(\cdot) \geq 0$), weakly concave ($u''(\cdot) \leq 0$) on the domain $[0, \infty]$, which implies $\mu(\cdot)$ is increasing, weakly concave for $X > 0$ and weakly convex for $X < 0$.

The gain-loss utility function allows for behaviors which cannot be explained in a simple Expected Utility framework (which only assumes a concave utility function). First, the reference point and the distance from the reference point in the gain-loss utility function creates additional utility changes compared to the utility level under Expected Utility Theory. In our model, the agent's utility can be significantly influenced by the expectation (specifically, *p.d.f.*) for future allowance prices (reference prices) and by the difference between the expected price and the current price. For example, if the seller faces higher expected price in the future compared to the current price, then her gain-loss utility will generate negative changes

[6] If $\eta \rightarrow +\infty$, $U(W)$ in equation (1.1) is only composed of a Kahneman-Tversky value function (1992) (Guo et al., 2016).

in her utility. Second, given the agent's gain-loss utility ($\eta > 0$), loss-averse preference causes an additional decrease in gain-loss utility. That is, if the agent is loss averse ($\lambda > 1$), then her gain-loss utility will decrease with loss aversion (See the proof in Appendix A.1.1). Thus, reference dependence ($\eta > 0$) and loss aversion ($\lambda > 1$) in our model will capture behavioral characteristics which cannot be seen in an Expected Utility framework.

The next properties, which are generated by properties of forward-looking reference points, are about how the gain-loss utility changes when the distribution of the reference point changes. Here, we can apply notions of stochastic dominance (the first-order stochastic dominance (*F.O.S.D.*) theorem and the second-order stochastic dominance (*S.O.S.D.*) theorem) to our gain-loss utility function.[7] This allows someone to determine the preference between cases with different *c.d.f.* in the gain-loss utility function. Since our gain-loss utility function is increasing but not globally concave, we can apply *F.O.S.D.* theorem to the gain-loss utility, but we cannot for *S.O.S.D.* theorem. However, if we have interests in simple, reasonable distributions of the reference point like the uniform, normal or student-t distribution, Proposition A.1 of Appendix A.1.3 can be applied to the gain-loss utility.

F.O.S.D. theorem is related to the change in the mean of the reference point (expected future price) and in our model we can use this theorem when the *p.d.f.*s of the reference point moves parallelly. For example, when the distribution of the reference point r moves parallelly, if the mean of r increases and X thus increases (decreases), then the gain-loss utility will increase (decrease) by *F.O.S.D.* theorem. Proposition A.3 is related to the change in the variance of the distribution with the same mean and in our model, we use this theorem when the variance of the reference points changes. For example, as the variance of the reference points increases, the agent's gain-loss utility decreases.[8]

[7] The definitions and the theorems for *F.O.S.D.* and *S.O.S.D.* can be seen in Appendix A.2.

[8] In Proposition A.1 of Appendix A.1.3, the link between the variance of the distribution and the preference is based on the "mean-preserving spread" (*M.P.S.*) property on the assumption of the *c.d.f.* F and G. For our gain-loss utility, although some restrictions are imposed on the *c.d.f.* F and G, there in no restriction on the *M.P.S.* property. So, we can conclude that as the variance of the reference points increases with simple, reasonable restrictions of F and G, the agent's gain-loss utility decreases.

1.2.2. The agent's trading behavior

A regulator generally establishes a cap-and-trade system with banking to regulate the level of emissions in the economy. To comply with the policy, each firm is required to surrender allowances equivalent to its current emissions at the end of each compliance period. For the policy's effectiveness, the regulator usually sets a penalty for compliance failure that is much larger than the potential benefits generated from compliance failure. Under this policy setting, firms with a surplus of allowances (which we will refer to as a "surplus position") can sell the allowances or carry them over to next year or period (which is called "banking"). For firms emitting more than their allowances ("shortage position"), they can purchase allowances from the market or borrow them against their future allocation (borrowing) but in our model borrowing is not allowed. We assume that all the firms are open to speculative trading, but no firm has the market power to affect the competitive market.

If not for compliance requirements, the allowance market would be akin to the market for a non-depreciating storable good. Compliance requirements lead to agent behaviors that are unique to cap-and-trade. Given the high penalty for compliance failure, market players will be particularly sensitive to the risk of facing a market shortage. Therefore, we divide the analysis into two cases: when the agent expects sufficient supply of allowances in the market, and when the agent expects a market shortage. For simplicity we consider a two-period model. Although we consider multiple periods, our implications do not change.

<u>*Basic setup*</u>

Let us denote Q_t^i as the free allocated allowances, q_t^i as the emissions in t period, $S_t^i(= Q_t^i - q_t^i)$ as the surplus of allowances for t period, Ts_t^i as the volume of allowance sales in t period, and Tb_t^i as the volume of allowance purchases in t period. Suppose that Q_t^i and Q_{t+1}^i were allocated before the implementation periods $(t, t+1)$ in advance and each firm is fully compliant with the regulation, and hence surrenders allowances equal current emissions. We also assume that each firm forms the banking demand before the end of t period, Ba_t^i, which implies that the trading demand at t period is $Ts_t^i = S_t^i - Ba_t^i$. Let us denote the purchase demand as Tb_t^i regardless of the purpose of allowance purchases. Following equation (1.1) and (1.2), our utility maximization problem starts from the following functional form:

$$U^i(W^i) = W^i + \eta \cdot \int \mu(X \mid r)dF(r) = W^i + \eta \cdot \int_{W>r} u(X)f(r)dr + \eta \cdot \lambda \int_{W<r} -u(-X)f(r)dr \tag{1.3}$$

In our model, we need to define payoffs (W^i) and the reference point (r) for X ($= W^i - r$) in our gain-loss utility. The firm's payoffs (W^i) will be the sum of the profits added or subtracted under the cap-and-trade system (W_T^i) and the profits from general business activities (W_{NT}^i).[9] Each firm has two kinds of payoff functions (W^i) for firms' available options at the period t as follows:

$$\begin{aligned} W_{seller}^i &= W_{NT}^i + W_T^i(Ts_t^i) = W_{NT}^i + Ts_t^i p_t + (S_t^i - Ts_t^i + S_{t+1}^i)\beta E(p_{t+1}) \\ W_{buyer}^i &= W_{NT}^i + W_T^i(Tb_t^i) = W_{NT}^i - Tb_t^i p_t + (S_t^i + Tb_t^i + S_{t+1}^i)\beta E(p_{t+1}) \end{aligned} \tag{1.4}$$

where β is the discount factor, $0 \leq Ts_t^i \leq S_t^i$, and $0 \leq Tb_t^i \leq \bar{B}_t^i$ where $\bar{B}_t^i$ is the budget constraint for each firm in period t. Here, we are interested in tendencies not to be willing to sell or buy. Considering agents' not-willing-to-trade tendencies, we set the reference point as the payoffs when the agent does not trade in the current period. In this situation, the agent banks all their surplus of allowances (S_t^i) into the market in period $t+1$ ($r = (S_t^i + S_{t+1}^i)\beta p_{t+1}$). Then, $X = W^i - r$ is $X_{Ts}^i = Ts_t^i\,(p_t - \beta p_{t+1})$ for a seller and $X_{Tb}^i = Tb_t^i(\beta p_{t+1} - p_t)$ for a buyer. Then, equation (1.3) can be modified into equation (1.5).

$$\begin{aligned} U_{seller}^i &= W_{NT}^i + W_T^i(Ts_t^i) + \eta \int_{p_t > \beta p_{t+1}} u\left(Ts_t^i\,(p_t - \beta p_{t+1})\right) dF(\beta p_{t+1}) - \eta\lambda \int_{p_t < \beta p_{t+1}} u\left(-Ts_t^i\,(p_t - \beta p_{t+1})\right) dF(\beta p_{t+1}) \\ U_{buyer}^i &= W_{NT}^i + W_T^i(Tb_t^i) + \eta \int_{\beta p_{t+1} > p_t} u\left(Tb_t^i(\beta p_{t+1} - p_t)\right) dF(\beta p_{t+1}) - \eta\lambda \int_{\beta p_{t+1} > p_t} u\left(-Tb_t^i(\beta p_{t+1} - p_t)\right) dF(\beta p_{t+1}) \end{aligned} \tag{1.5}$$

Here, βp_{t+1} is an individually heterogeneous random variable with the *c.d.f.* (F) and the reference price is endogenously determined by each agent's expectation. Note that the agent's problem can be reformulated as a problem of the forward-looking reference price (βp_{t+1}). This implies that the decision on the

[9] More specifically, $W_{NT}^i = E\sum_{s=t}^{t+1}(p_s^y y_s(k_s, l_s, q_s) - r_s k_s - w_s l_s)$ where p_s^y is the price of output y at the period s, $y_s(k_s, l_s, q_s)$ is the output function with capital (k_s), labor (l_s), and emission (q_s) as inputs, r_s is the capital price, and w_s is the labor price. $W_T^i(Ts_t^i) = p_t Ts_t^i + \beta E(p_{t+1})\{(Q_t^i - q_t^i) - Ts_t^i + (Q_{t+1}^i - q_{t+1}^i)\}$ for sellers, and $W_T^i(Tb_t^i) = -p_t Tb_t^i + \beta E(p_{t+1})\{(Q_t^i - q_t^i) + Ts_t^i + (Q_{t+1}^i - q_{t+1}^i)\}$ for buyers. Note that for the firm's payoff (W^i), W_T^i and W_{NT}^i are additively separable in terms of Ts_t^i for sellers or Tb_t^i for sellers.

transaction largely depends on the comparison between the current price and his expected price in the future, where differences between both prices cause additional utility or disutility through gain-loss utility function.

Case 1 – when sufficient market supply is expected

In this section, we consider the case that although each firm faces the situation that the emissions of each firm exceed the number of allowances that it owns, the agent can easily obtain their allowance shortfalls in the market. That is, this case can explain the market or policy situation that allowances can be stably and steadily supplied to the firms. We first consider the payoffs-level utility function without the gain-loss utility function ($\eta = 0$). This case will be the basis for our analysis. Each firm has the same payoff functions as those in equation (1.4) at the period t, and all the decisions to bank, sell, and purchase allowances depend on the first order condition (*F.O.C.)* with respect to the volume of sales (Ts_t^i) or purchases (Tb_t^i), which is the intertemporal no arbitrage condition ($p_t = \beta E(p_{t+1})$).[10] Note no difference between $MWTA^i$ and $MWTP^i$ and no endowment effects ($p_t = MWTA^i = MWTP^i = \beta E(p_{t+1})$).

From here, we consider our reference-dependent model *(*$\eta > 0$*)* and an agent's *c.d.f.* (F) of βp_{t+1}. For simplicity, we assume $u(\cdot) = (\cdot)^\sigma$ $(0 < \sigma \leq 1)$ for gain-loss utility, which is a generalization of the functional form proposed by Tversky and Kahneman (1992). Then, through *F.O.C.s* with respect to Ts_t^i and Tb_t^i, we can derive the following simplified implicit functions (H^i) of the individual marginal willingness to accept ($MWTA^i$) and marginal willingness to pay ($MWTP^i$).

$$\begin{aligned} H_{seller}^i &= p_t - \beta E(p_{t+1}) + \eta_s \int_{p_t<\beta p_{t+1}} (p_t - \beta p_{t+1})^\sigma \, dF(\beta p_{t+1}) - \eta_s \lambda \int_{p_t>\beta p_{t+1}} \big(-(p_t - \beta p_{t+1})\big)^\sigma \, dF(\beta p_{t+1}) = 0 \\ H_{buyer}^i &= \beta E(p_{t+1}) - p_t + \eta_b \int_{p_t>\beta p_{t+1}} (\beta p_{t+1} - p_t)^\sigma \, dF(\beta p_{t+1}) + \eta_b \lambda \int_{p_t<\beta p_{t+1}} \big(-(\beta p_{t+1} - p_t)\big)^\sigma \, dF(\beta p_{t+1}) = 0 \end{aligned} \tag{1.6}$$

where $\eta_s = \eta\sigma\big(Ts_t^i\big)^{\sigma-1}$ and $\eta_b = \eta\sigma\big(Tb_t^i\big)^{\sigma-1}$. Using the Leibniz integral rule and intermediate value theorem with a symmetric distribution of βp_{t+1}, we can analytically induce Proposition 1.1 (See the details in Appendix A.1.4).

[10] The implication of this condition is simple. If $p_t > \beta E(p_{t+1})$, sales are more favorable. If $p_t < \beta E(p_{t+1})$, banking and speculative purchases are more favorable.

Proposition 1.1 *When the agent expects that the market allowance supply is large enough in the next period, if* $\eta > 0$ *and* $\lambda > 1$ *with a symmetric distribution of* βp_{t+1} *(F), then there is a gap* $MWTA^i$ *and* $MWTP^i$*, that is,*

$$MWTA^i = \beta E(p_{t+1}) + K_s \quad (K_s > 0) \text{ for a seller}$$

$$MWTP^i = \beta E(p_{t+1}) - K_b \quad (K_b > 0) \text{ for a buyer}$$

Proposition 1.1 indicates that under the expectation of sufficient supply, the reference dependence ($\eta_s, \eta_b > 0$) and loss aversion ($\lambda > 1$) lead to a gap between MWTP and MWTA for allowances. The magnitude of $MWTA/P^i$ depends on the degree of the relative weight of gain-loss utility (η_s, η_b), the degree of loss aversion (λ), and the probability distribution of the agent's expected future prices for allowance (See the comparative analysis in Appendix A.1.4). That is, given $\eta_s, \eta_b > 0$, if the agent is loss-neutral ($\lambda = 1$), there is no MWTA–MWTP disparity, and if $\lambda > 1$, the more loss averse, the higher his $MWTA^i$ for a seller and the lower his $MWTP^i$ for a buyer, which leads to larger MWTA–MWTP gap ($\frac{dMWTA^i}{d\lambda} > 0$ and $\frac{dMWTP^i}{d\lambda} < 0$). Given $\lambda > 1$, the MWTA–MWTP gap increases in the weight of gain-loss utility ($\frac{dMWTA^i}{d\eta_s} > 0$ and $\frac{dMWTP^i}{d\eta_b} < 0$). For example, if the agent pays more attention on gains or losses caused by the transaction of allowances rather than those from general activities of the firm, the agent will put more emphasis on gain-loss utility (higher η_s, η_b).

Case 2 – when insufficient market supply is expected (shortage)

Under the sufficient allowance supply, although the firm is in the 'shortage' position and faces the compliance demand, the agent can easily obtain the shortfalls from the market, thus keeping the lower $MWTP^i$ than $\beta E(p_{t+1})$ as in Proposition 1.1. However, as the surplus of allowances in the market decreases, firms in the "shortage position" will have a hard time finding for sellers who offer the price (below $\beta E(p_{t+1})$) that they want.[11] Then, the firm's problem will be to search the firm with $MWTA^j$ as low as possible, not to maintain his own $MWTP^i$ below $\beta E(p_{t+1})$. If the firm has the compliance demand under high penalty for compliance failure, his reference price will be switched from βp_{t+1} into the expectation of the next offer price p_t^y. That is, depending on other players' $MWTAs$ rather than her own expectation ($\beta E(p_{t+1})$), current compliance demanders get less elastic to price as their reservation prices become high (See the details in Appendix 4.1.5).

The fact that compliance demanders may buy allowances from the market even at high prices will affect the agent's behavior even without the compliance demand in the current period. That is, they will consider the possibilities (c) of price increases (K_{comp}) caused by future compliance demanders, expecting the market supply in the next period.[12] Let $\bar{S}_{t+1}$ act as the cut-off surplus level in $t+1$ period such that the market price would not be affected by endowment effects in the market.[13] Let us denote $\beta K_{comp}(> 0)$ as the additional increase in his expected price caused by endowment effects and the probability that the market supply in the $t+1$ period is less than $\bar{S}_{t+1}$ as $c = C(S_{t+1} < \bar{S}_{t+1})$ where $C(\cdot)$ is the *c.d.f.* of S_{t+1}. Then, the expectation of his switched reference price $\beta E(\hat{p}_{t+1})$ will be[14]:

$$\begin{aligned} \beta E(\hat{p}_{t+1}) &= (1-c)\beta E(p_{t+1}) + c \times \beta(E(p_{t+1}) + K_{comp}) \\ &= \beta E(p_{t+1} + K') \qquad \text{where } K' = cK_{comp} > 0 \end{aligned} \tag{1.7}$$

That is, reference prices of both sellers and buyers will increase from βp_{t+1} to $\beta(p_{t+1} + K')$ ($K' > 0$). Note that in equation (1.7) $E(p_{t+1}) + K_{comp}$ is the expected price under supply shortage in the next period, such as the price under market stabilization measures and the penalty for compliance failure as a

[11] That is, as firms move toward the deadline of their compliance, compliance demanders will be under such psychological pressure that they might pay high costs for their shortfalls because their bargaining powers in the trading get weaker as time goes by.

[12] Specifically, under the expectation of insufficient market supply in the next period, potential compliance demanders in the next period will have concerns that they may face the compliance demand in the next period $t+1$, and speculative traders will expect future allowance prices which may increase driven by potential compliance demanders.

[13] We will define $\bar{S}_{t+1}$ as the "effective market supply" and discuss it in more detail in section 1.3.2.

[14] We simply follow the convex combination updating rule of reference point given the rational agent (Diez and Venmans, 2019; Gagnon-Bartsch and Bushong, 2019).

worst case. That is, probabilities that allowances may be exhausted in the future (c) and price increases caused by future compliance demanders (K_{comp}) are additionally considered for formulating both MWTAs and MWTPs. Through the same methods of proof as in Proposition 1.1, we can easily obtain the Proposition 1.2. Proposition 1.2 implies that although the agent is not in the 'shortage position' at the current period, both $MWTA^i$ and $MWTP^i$ would increase, when the agent expects that the market supply will not be large in the next period.[15]

Proposition 1.2 *Given $\eta > 0$, $\lambda > 1$ and an agent without compliance demand in the current period, if the agent expects that the market allowance supply is not large enough in the next period, then*

(1) there is a gap $MWTA^i$ and $MWTP^i$,

$$\widehat{MWTA^i} = \beta E(p_{t+1} + K') + \widehat{K}_s \quad \left(\widehat{K}_s > 0\right) \text{ for a seller}$$

$$\widehat{MWTP^i} = \beta E(p_{t+1} + K') - \widehat{K}_b \quad \left(\widehat{K}_b > 0\right) \text{ for a buyer}$$

(2) given that p.d.f.s. of βp_{t+1} and $\beta(p_{t+1} + K')$ satisfy the assumptions on p.d.f. in Proposition 1.3 and that the variance of $\beta(p_{t+1} + K')$ is higher than that of βp_{t+1}, for $MWTA^i$ in Proposition 1.1,

$$\widehat{MWTA^i} > MWTA^i \text{ for a seller}$$

Proof. We can prove Proposition 1.2.(1), using the same methods as those in proofs of Proposition 1.1. In the case of Proposition 1.2.(2), if the variance of $\beta(p_{t+1} + K')$ is higher, Proposition 1.2.(2) will hold by propositions 1.1 and 1.3 (See the below additional case of section 1.2.2). □

Note that if the agent expects the higher $c = C(S_{t+1} < \bar{S}_{t+1})$ and βK_{comp}, then both $MWTA^i$ for a seller and $MWTP^i$ for a buyer can be abnormally increase. In this situation, the agent will stick with

[15] There are conditions that Proposition 1.2.(2) holds even without the assumptions of *p.d.f.* for βp_{t+1} and $\beta(p_{t+1} + K')$. If $\beta E(p_{t+1} + K') \geq MWTA^i$, Proposition 1.2.(2) will naturally hold since $\widehat{K}_s > 0$. Although $\beta E(p_{t+1} + K') < MWTA^i$, if the *p.d.f.* of βp_{t+1} increases parallelly into the *p.d.f.* of $\beta(p_{t+1} + K')$, Proposition 1.2.(2) will hold by Proposition A.1 of Appendix A.1.3.

excessive banking instead of selling allowances. Although the agent expects the low $c = C(S_{t+1} < \bar{S}_{t+1})$, then $MWTA^i$ can increase by the update of the reference price due to high K_{comp}. Specifically, if the rule on allowance prices for $S_{t+1} < \bar{S}_{t+1}$ is not clear, then this may cause the agent to expect the highest prices permitted in the system as $E(p_{t+1}) + K_{comp}$. Also, S_{t+1} has uncertainties, which implies that although the mean of S_{t+1} is higher than $\bar{S}_{t+1}$, his probability distribution of S_{t+1} may have a large variance. It may lead to the large distribution for $S_{t+1} < \bar{S}_{t+1}$ and high $c = C(S_{t+1} < \bar{S}_{t+1})$ in equation (1.7), which will increase both $MWTA^i$ and $MWTP^i$ by Proposition 1.2.

Additional case – when the agent expects the higher variance of the price in the future

If the future price is certain, there is no *MWTA–MWTP* disparity because $K_s, K_b = 0$ in Proposition 1.1. Under the uncertain future price, we can see that the gap between $MWTA^i$ and $MWTP^i$ increases with loss aversion and reference dependence in Proposition 1.1. Therefore, we can intuitively infer that $MWTA/P^i$ increase with the degree of the uncertainty (variance), considering the applicability of *S.O.S.D.* theorem (Theorem A.2 of Appendix A.2) which indicates the relationship between the variance and the expected utility of a random variable. However, since our gain-loss utility is not globally concave, *S.O.S.D.* theorem is not directly applicable to the gain-loss utility. Instead, if we are simply interested in the general cases of the probability distribution like a normal or a uniform distribution, we can derive the following proposition on the relationship between $MWTA/P^i$ and variance of βp_{t+1} by introducing the similar restrictions in Proposition A.1 of Appendix A.1.3.

Proposition 1.3 *Given $\eta > 0$ and $\lambda > 1$, suppose that the c.d.f. F and G of βp_{t+1} have the same mean $\beta E(p_{t+1})$. Also, assume that $F(\beta p_{t+1}) \le G(\beta p_{t+1})$ if $\beta E(p_{t+1}) \le \beta p_{t+1}$.*

Then, if their p.d.f. f and g are symmetric around the mean $\beta E(p_{t+1})$, then, the higher variance of βp_{t+1} around $\beta E(p_{t+1})$, the higher $MWTA^i$ for a seller and the lower $MWTP^i$ for a buyer.

Proof. See the details in Appendix A.1.6. ☐

That is, under the general assumptions for f and g like a normal, a student-t or a uniform distribution with the same mean $\beta E(p_{t+1})$, the higher variance of βp_{t+1}, the higher $MWTA^i$ for a seller, and the lower $MWTP^i$ for a buyer by Proposition 1.3.

Note that the problem can be exacerbated if agents have the higher price variance with uncertain $c = C(S_{t+1} < \bar{S}_{t+1})$ and K_{comp} in equation (1.7) under insufficient market supply. Specifically, if the price rule for the shortage of market supply is not clear (uncertain K_{comp}), it will lead to the higher variation for the loss part in the distribution of βp_{t+1} for the seller, significantly causing the higher expected prices for the loss part and thus the higher $MWTA^i$. Furthermore, the variability of future prices is meaningful for the length of forward-looking period considered for decision making. If firms need the long-term investments for substantial abatement efforts and the management of allowances is required during the investment period, the forward-looking period will become longer. In this case, the short-term cap can cause the difficulty of prediction beyond higher variation of future prices. This proposition also has important implications on uncertainties of marginal abatement costs in the next period since βp_{t+1} is directly related to the expected marginal abatement cost in $t + 1$ period.

1.2.3. Numerical illustrations

Numerical illustrations will be helpful to understand the magnitude of the endowment effects on the trading behaviors. Considering that the buyer's $MWTP^i$ largely depends on the seller's $MWTA^i$ in the case of insufficient market supply (See Appendix A.1.5), we will investigate how the seller's $MWTA^i$ changes along with the arbitrary parameter values, based on Proposition 1.1-1.3. For comparison of $MWTA^i$ in each situation, our output indicator R_{MWTA} is expressed as the relative $MWTA^i$ to his own expected price in the next period:

$$R_{MWTA} = {}^{MWTA^i}\!/_{\beta E(p_{t+1})} \tag{1.8}$$

The denominator $\beta E(p_{t+1})$ means the expected price discounted at the present value under the expectation of sufficient market supply. The numerator $MWTA^i$ will be numerically approximated based on the implicit function of p_t in equation (1.9), which indicates F.O.C. of the seller's problem in equation (1.6).

$$MWTA^i = \beta E(p_{t+1}) + \eta_s \lambda \int_{p_t<\beta p_{t+1}} \left(-(p_t - \beta p_{t+1})\right)^{\sigma} dF(\beta p_{t+1}) - \eta_s \int_{p_t>\beta p_{t+1}}^{0} (p_t - \beta p_{t+1})^{\sigma} dF(\beta p_{t+1}) \qquad (1.9)$$

In numerical simulations, unlike assumptions for the symmetric distribution of βp_{t+1} in Proposition 1.1-1.3, we consider that the agent has a log-normal distribution for βp_{t+1} to capture the positivity assumption of allowance prices. Following Barberis (2013), the default parameter values for gain-loss utility are chosen as follows: $\lambda = 2.25$ and $\sigma = 0.88$, and $\eta_s = 0.5, 1, 2, 5, +\infty$.[16] For heterogeneity of λ, we also apply several λ values in the previous literature to our model (The estimation results are presented in Table A.3.1 of Appendix A.3).[17] We also assume that $log\,(\beta p_{t+1}/\beta E(p_{t+1}))$ follow the normal distribution with the mean 0 and variance 0.20.[18]

Figure 1.1 shows how R_{MWTA} changes as $\eta_s > 0$ (Figure 1.1(a)) and $\lambda > 1$ (Figure 1.1(b)) change. For the effect of η_s, R_{MWTA} increases with both η_s as in analytical proofs. However, R_{MWTA} is more sensitive to changes in η_s below $\eta_s = 1$, while it converges to the specific value as η_s goes to $+\infty$. Given the default values ($\lambda = 2.25$, $\sigma = 0.88$), the agent's R_{MWTA} changes in η_s, ranging from 1.061 ($\eta_s = 0.5$) to 1.146 ($\eta_s = +\infty$). R_{MWTA} also sensitively increase with λ. If λ increases to 3.5 (Heutel, 2019), R_{MWTA} significantly increases, ranging from 1.112 ($\eta_s = 0.5$) to 1.241 ($\eta_s = +\infty$).

Next, in the case that the agent expects the insufficient market supply (which is related to Proposition 1.2), recall that there are "reference price switching effects" where reference price will increase to $\beta E(p_{t+1} + K') = (1-c)\beta E(p_{t+1}) + c \times \beta(E(p_{t+1}) + K_{comp})$ in equation (1.7). We assume that the agent expects the maximum price acceptable in the systems to be at the level of $R_{MWTA} = 4$ when $S_{t+1} <$

[16] Since η_s can be heterogeneous on $[0, +\infty]$, we consider multi-values for η_s.

[17] Barberis (2013); Tanaka et al. (2010); Liu (2013); Heutel (2019)

[18] As for the value of the variance (0.20), we use the variance of $log\,(\beta p_{t+1}/p_t)$ for KAU (Korea Allowance Unit) price at first business day in September in the Korean Emission Trading Scheme (K-ETS). Under the expectation of sufficient market supply, since the effect of the gap between the MWTA and MWTP on p_t at the current period will not be significant (we will see this in section 1.3.1), $\beta E(p_{t+1})$ can be assumed to be equal to p_t at the current period. Next, KAU (Korea Allowance Unit) prices at first business day in September can be justified in that these prices indicate prices stabilized with sufficient market supply after market stabilization measures for price hikes. Also, we assume the 3-year forward-looking period and annual subjective discount factor β is chosen as 0.98 (which implies the annual interest rate of 2%). If we consider the longer forward-looking period, then the value of the variance may be higher.

$\bar{S}_{t+1}$ $(\beta(E(p_{t+1}) + K_{comp}) = p^{max})$.[19] We consider that prices follow the log-normal distribution with the switched mean and the same variance as above.[20]

Figure 1.2(a) shows how R_{MWTA} changes as c increases, given $\lambda = 2.25$ and $\sigma = 0.88$. Note that if the shortage of market supply is significantly expected, R_{MWTA} can increase significantly with c. For example, when $c = 0.5$, R_{MWTA} can be high (2.643 for $\eta_s = 0.5$ and 2.864 for $\eta_s = +\infty$). As for low probability of shortage, the agent may be pessimistic where the probability of the low state is overweighted, and the probability of the high state is underweighted. Assuming the inverse-S shaped probability weighting function from Prelec (1998) ($\pi(c) = 1/exp\,[ln\,(1/c)]^{\varphi}$) and $\varphi = 0.75$ (Tanaka et al., 2010; Heutel, 2019), we can see the higher R_{MWTA} even under the small c (See Figure A.3.1 of Appendix A.3).

Figure 1.2(b) shows how R_{MWTA} is sensitive to changes in the standard deviation (Std) of $log\,\beta p_{t+1}/\beta E(p_{t+1})$ (σ_ε). This is directly related to the cases when the probability of shortage (c) or prices (K_{comp}) under the shortage of market supply also has large variation (which is related to Proposition 1.3). We can see R_{MWTA} is highly sensitive to changes in the Std (σ_ε) of $log\,\beta p_{t+1}/\beta E(p_{t+1})$ even under small probability of the shortage ($c = 0.1$). For example, given $\eta_s = 1$, $\lambda = 2.25$, $\sigma = 0.88$, and $c = 0.1$, if the Std increases to 2 on the scale of $\frac{\beta p_{t+1}}{\beta E(p_{t+1})}$, R_{MWTA} increases to 1.712.

Next, considering the clear rule for allowance price when $S_{t+1} < \bar{S}_{t+1}$, we investigate the effects of the safety valve as a potential alternative for price hikes under the expectation of insufficient market supply.[21] Given $\lambda = 2.25$ and $\sigma = 0.88$, we assume that the system has price collar where the ceiling price ceiling and flooring price are censored at the level of $R_{MWTA} = 2$ and $R_{MWTA} = 0.5$, respectively.[22]

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[19] This corresponds to the level of penalty for compliance failure which is usually three times the average allowance price for the specific period. Also, if firms are additionally required to pay compliance costs even after firms pay their penalties, firms' expected cost will become much higher.

[20] This is just to identify the effects of c on R_{MWTA}, under the condition that other parameters, including the variance of $log\,(\beta p_{t+1}/\beta E(p_{t+1}))$, are given.

[21] For the safety valve as a potential alternative to endowment effects, we will cover it in more detail in section 1.4.

[22] This implies that when the price reaches the ceiling price, allowances can be continuously supplied from sources such as the market reserve or allowances purchased from outside the system by the regulator (this is so called 'hard price ceiling approach'). In the case that a limited number of allowances are supplied from the above sources ('soft price ceiling'), the effect of c or the Std of $log\,\beta p_{t+1}/\beta E(p_{t+1})$ depends on the size of the supply limit.

Through figures 1.3(a) and 1.3(b), which show the effect of $c = C(S_{t+1} < \bar{S}_{t+1})$ and the effect of the Std of $log\, \beta p_{t+1} / \beta E(p_{t+1})$ (σ_ε), we can see that the ceiling price can not only limit R_{MWTA} by lowering the level of βK_{comp} (into the level of $R_{MWTA} = 2$ under our assumption) in equation (1.7) but also suppress the effects of η_s and λ by lowering the expected value for the negative part in equation (1.9). However, note that below the ceiling price, the safety valve cannot clearly remove the "reference switching effect" caused by potential compliance demands in the future. Although we alternatively consider a truncated normal distribution which is bounded from 0, the implications do not change much (The results for the case of a truncated normal distribution can be seen in figures A.3.2-4 of Appendix A.3).

1.3. Endowment Effects and the Allowance Market

1.3.1. The effects of reference-dependent behaviors on the market

In this section, we focus on how endowment effects caused by reference-dependence and rational reference-switching influence the market equilibrium in terms of equilibrium supply/demand and equilibrium price. In the literature, there are two kinds of well-known conceptual frameworks to analyze the market performance in the cap and trade: the efficiency framework and the cost-effectiveness framework (Fuss et al., 2018). In the former, the allowance price and the social welfare maximizing cap are determined at the point such that the marginal damage of emission is equal to the marginal abatement cost, while in the latter the allowance price depends on the level of a given cap and the marginal abatement cost.

However, endowment effects built on reference-dependence are related to agents' expectations with the forward-looking approach, neither marginal damage nor marginal abatement cost. That is, the above frameworks focus just on behaviors for emission or abatement, not trading behaviors for allowances in the market. Therefore, our study will apply the supply/demand curve framework based on *MWTP* and *MWTA* for allowances. Our framework is strongly associated with the views in the recent literature (Lintunen and Kuusela (2018); Kuusela and Lintunen (2019); Borenstein et al., 2019; Aldy & Armitage, 2020; Pizer & Prest (2020); Quemin and Trotignon (2021)) that in a dynamic setting with unlimited banking, allowance prices are significantly affected by participants' expectations with the intertemporal no arbitrage condition ($p_t = \beta E(p_{t+1})$).

In general goods, the price on the supply curve implies the minimal price which the supplier is willing to accept when "selling additional one unit", which indicates the *MWTA* for each volume of sales in the market. Also, the price on the demand curve implies the maximum price which the demander is willing to pay when "buying additional one unit", which indicates the *MWTP* for each volume of purchases in the market. Therefore, in the allowance market, the supply curve (S_{WTA}) and the demand curve (D_{WTP}) can be obtained by accumulating the *MWTA* and *MWTP* for each allowance unit of all players from left to right in the lower order of *MWTA* considering each firm's budget constraints, respectively.

Let us denote D_{comp} as the individually aggregated excess emissions of the market in the current period, where $D_{comp} = \sum\left(q_t^i - Q_t^i\right)$ for each i such that $q_t^i > Q_t^i$. Recall that when each firm's emissions exceed free allocated allowances at the current period, the firm need to pay the high penalty for non-compliance. This can create the demand curve inelastic on D_{comp} or less elastic around D_{comp}. Since the supply and demand curve in our framework is related to the expected price in the future, we assume that at the current period the entire market is in a sufficient surplus position ($Q_t > q_t$), where Q_t and q_t denote the level of the entire cap and the entire emissions in cap and trade. Therefore, given that firms satisfy their compliance obligation, equilibrium supply/demand (V_t) should be larger than D_{comp}. Figures 1.4 shows the supply and demand curve for allowances on our conceptual framework. Without gain-loss utility ($\eta = 0$), the equilibrium price (p_t^0) and equilibrium supply/demand (V_t^0) in the market are determined at the point such that the supply curve (S_{WTA}^0) and demand curve (D_{WTP}^0) meet each other.

For the situation that market participants are reference-dependent ($\eta > 0$ and $\lambda > 1$), we also consider two cases: i) when sufficient market supply for allowances is expected in the next period, and ii) when insufficient market supply is expected in the next period. In the first case (Figure 1.4(a)), it is relatively easy for firms with compliance demands to obtain the allowances in the market, so that all the firms have no concerns that the equilibrium supply/demand (V_t^*) will be binding to D_{comp}. As in Proposition 1.1, most buyers try to have $MWTP^i = \beta p_{t+1}E(p_{t+1}) - K_{Tb}$, while most sellers try to have $MWTA^i = \beta E(p_{t+1}) + K_{Ts}$, where $K_{Tb}, K_{Ts} > 0$. Then, the demand curve moves down from D^0 to $D^{\eta,\lambda}$, while the supply curve moves up from S^0 to $S^{\eta,\lambda}$. As a result, the equilibrium supply/demand decreases from V^0 to $V^{\eta,\lambda}$ (above D_{comp}), while the equilibrium price changes relatively little from p^0 to $p^{\eta,\lambda}$.[23] Here, sellers' reference dependences and loss aversions work to drive up the market allowance price, but buyers' preferences can also offset the effect of this increased price, and thus the changes in the market price will not be significant.

Now we consider the case that the participants expect that the market supply may not be sufficient in the next period (Figure 1.4(b)). In this case, as shown in the case 2 of section 1.2.2, compliance demanders in the current period will be likely to accept the current offers even though currently offered prices are higher than their own expected prices in the next period. Furthermore, although firms do not have the compliance demands in the current period, they will consider the probability that the market demand may exceed the market supply in the next period ($Q_{t+1} + Ba_t < q_{t+1}$). It will cause them to have the higher expected price in the next period as in equation (1.7) ($\beta E(\hat{p}_{t+1}) = \beta E(p_{t+1} + K')$, where $K' > 0$) due to the "reference switching effect" driven by expectations of insufficient market supply in the next period and potential compliance demands. That is, they have the effects of increasing both supply and demand curves ($D^0_{WTP}, S^0_{WTA} \rightarrow D^{ref}_{WTP}, S^{ref}_{WTA}$; $D^{ref}_{WTP}, S^{ref}_{WTA} \rightarrow D_{WTP}^{ref+\eta,\lambda}, S_{WTA}^{ref+\eta,\lambda}$ with the effects of η and λ), which will significantly increase market price ($p^0 \rightarrow p^{ref+\eta,\lambda}$).

Furthermore, when agents expect higher variations of future prices along with the current supply shortage, the situations get worse. The higher variance of βp_{t+1} (or marginal abatement cost in $t+1$ period) would lead to an increase in $MWTA$ for sellers and a decrease in $MWTP$ by Proposition 1.3. Then, the supply curve goes up, while the demand curve goes down ($D_{WTP}^{ref+\eta,\lambda}, S_{WTA}^{ref+\eta,\lambda} \rightarrow D_{WTP}^{ref+\eta,\lambda-\alpha}, S_{WTA}^{ref+\eta,\lambda+\alpha}$) in Figure 1.4(c). The problem is when the equilibrium supply/demand are formulated around D_{comp} where the allowance demand becomes inelastic to allowance prices. Here, the

[23] Whether the equilibrium price increases or not will depend on the slope or shape of the demand curve and supply curve and their responsiveness to loss aversion.

equilibrium price will rise much more than the equilibrium price ($p^0 \rightarrow p^{ref+\eta,\lambda+\alpha}$). If expectations of insufficient supply continue for some period, agents would become habituated to higher banking demand (Figure 1.4(d)) ($p^0 \rightarrow p^{ref+\alpha+\eta,\lambda}$).[24] The habituation of banking will cause higher K' in equation (1.7) by increasing $E(V_{t+1}^{endow} \mid I)$ in section 1.3.2 and thus increasing $c = C(S_{t+1} < \bar{S}_{t+1})$ in equation (1.7).

The insufficient allowance supply case can be a serious problem even in terms of social welfare because endowment effects can cause a significant increase in the social cost for GHG mitigation along with excessive banked allowances. Here, the additional increase in social cost for the mitigation is due to agents' behavioral preferences caused by their expectations (concerns) of high compliance costs under insufficient market supply, not the direct changes in marginal benefit or marginal abatement cost. Furthermore, if factors such as βp_{t+1}, its probability distribution, η and λ get more individually heterogeneous, the price volatility will get higher.

1.3.2. Potential circumstances for endowment effects

In the previous section, we looked at the possibility that when agents expect that the future market supply is not sufficient or uncertain, it can affect the significant increase in the social cost of the mitigation which is driven by the "reference switching" of agents. In this section, we investigate possible circumstances in the real world that may result in expectations of insufficient supply or higher supply variance by looking into the individual expectation of the "effective market supply" at the next period. Also, to facilitate the effective preparations for the global climate issues, we will investigate the cases in the context of the implementation of the Paris Agreement. Given the individual information set (I^i), the expected "effective market supply" in $t+1$ period $E\left(S_{t+1}^{eff} \mid I^i\right)$ can be represented as follows:

$$E\left(S_{t+1}^{eff} \mid I^i\right) = E\left(Q_{t+1} - q_{t+1}^{BAU} + m_{t+1} + Ba_t - V_{t+1}^{endow} \mid I^i\right) \tag{1.10}$$

where I^i is a i's information set; Q_{t+1}, q_{t+1}^{BAU}, Ba_t and m_{t+1} are the cap, the business as usual emissions, the quantities banked from t period and the quantities of mitigation for the overall sector in $t+1$ period,

[24] These effects are similar to "the reference updating effects" in Dietz and Venmans (2019). That is, forward-looking agents will anticipate the banking level in the next period based on the previous banking levels.

and V_{t+1}^{endow} is the quantities not supplied by the endowment effects even under the sufficient market supply. If $E\left(S_{t+1}^{eff} \mid I^i\right)$ gets close to '0' or becomes less than '0' given the individual information set, *MWTAs* for sellers in the current period gets increased by the "reference switching effect"; thus, it will increase the current market equilibrium price. Here, we will take a closer look at each factor in equation (1.10) to find specific conditions for $E^i\left(S_{t+1}^{eff} \mid I^i\right) < 0$ or high variance of S_{t+1}^{eff}.

Total market surplus ($\boldsymbol{E(S_{t+1} = Q_{t+1} - q_{t+1}^{BAU} + m_{t+1} + Ba_t \mid I^i)}$): It is natural that if the total cap gets more and more strict, the total emissions are continuously increasing, or the mitigation is less price-elastic, then the participants will have concerns that the market will suffer from a shortage of allowances ($S_{t+1}^{eff} < 0$). One of the notable points is that these situations are becoming more and more real under the Paris Agreement. As global warming is occurring faster than projected, the Paris Agreement is urging urgent and ambitious actions; each country should try to comply the principle of progression for the NDC presented in the Article 4(3)[25] of the Paris Agreement, which will act as a burden in the position of the participants with compliance obligation under the cap-and-trade system. That is, agents' expectations (or concerns) on decreasing total market surplus have potentials to influence the effectiveness of the system.

Expected endowment effects ($\boldsymbol{E(V_{t+1}^{endow} \mid I^i)}$): As mentioned in the introduction section, there are various factors to cause the endowment effects in addition to our reference-dependent preferences. Each agent cannot get the accurate estimates of others' endowment effects in the next period, and $E(V_{t+1}^{endow} \mid I^i)$ may be estimated roughly based on his own information set (I^i). The information set of each agent includes other players' propensity, market structure (the number of participants, whether there are market dominant players, or market or policy uncertainties), or the history on the past performance. The more each agent expects the market to show the endowment effect overall, the smaller "effective market supply"

[25] *"Each Party's successive nationally determined contribution will represent a progression beyond the Party's then current nationally determined contribution and reflect its highest possible ambition, reflecting its common but differentiated responsibilities and respective capabilities, in the light of different national circumstances."*

(S_{t+1}^{eff}) he will anticipate. Note that endowment effects in the previous period can affect the agents' decisions in the next period.

Uncertainties for $\boldsymbol{Q_{t+1}}$, $\boldsymbol{q_{t+1}^{BAU}}$, $\boldsymbol{m_{t+1}}$: Although the $E\left(S_{t+1}^{eff} \mid I^{i}\right)$ is positive, if it has high variation especially toward losses in the distribution of S_{t+1}^{eff}, then it can increase $c = C(S_{t+1} < \bar{S}_{t+1})$ in equation (1.7), thus causing agents to be stuck in the risk of the short market supply and leading to the higher *MWTP/A* with Proposition 1.2. For example, we frequently see that participants in the long term just observe the market situations until more information about whether the market supply is likely to be sufficient or not is obtained throughout the periods of the system (Borenstein et. al., 2019). In the case of countries that start to make meaningful GHG mitigation efforts under the Paris Agreement and that initiate or are preparing the cap-and-trade system, their future emissions or growth rate would likely be uncertain because of unstable economic growth and policy environments. For those countries, uncertainties can be caused by the types of uncertain national GHG mitigation targets, which include the types of 'intensity targets' or relative targets for reducing emissions below 'business as usual' level (BAU target).[26] These targets not only inherently include ex-ante uncertainties on the target year's emissions.[27] Also, as for the mitigation effects (m_{t+1}), the abatement cost risk is only transmitted to the allowance price through the emissions (Stranlund et al., 2019). That is, if random shocks on the marginal abatement cost in the market are frequent, then agents would be likely to expect the higher volatility of βp_{t+1}.

Individual information set ($\boldsymbol{I^{i}}$): If even the basic information including the total cap, the remaining market reserve, the current price, or the volume of trade on the day is not shared with firms, $E\left(S_{t+1}^{eff} \mid I^{i}\right)$ would have a high variation as in the case of uncertainty. Furthermore, if the regulator does not share the

[26] Countries that have communicated an 'intensity target' account for approximately 4% among the total number of countries which have communicated the NDC, but they consist of major emitters in the developing countries such as China and Chile. Countries that have communicated a 'BAU target' account for approximately 45% which includes South Korea, Mexico, Columbia, Thailand, Indonesia, Thailand, and Vietnam. (UNFCCC, 2016, Aggregate effect of the intended nationally determined contributions: an update). All these countries which are given as examples are initiating or preparing the national wide cap and trade system (ICAP, 2019).

[27] Although the cap would be set long-termly, there will still exist uncertainties due to the possibility of potential cap modifications caused by updating the quantified level of national targets as the economic situations in the countries concerned change.

market and policy information in the cap and trade, firms which currently have the incomplete and inaccurate information are just waiting for the government announcement and new information. This is consistent with the Kollenberg and Taschni's argument (2016) and empirical evidence that the discount rate of market participants in the cap-and-trade system is a function of the regulator's policy announcements and is endogenous. In addition, if firms do not have credibility for the regulator and the policy consistency, then it would make it much more difficult for each individual to judge the appropriateness of the estimated information on each factor in equation (1.10).

Our paper suggests that market liquidity problems or endowment effects can occur enough even in well-functioning systems as well as those which developing countries are preparing and initiating. The concerns that there may be a shortage of future allowance supply and uncertainties here and there can be caused by various sources within or around cap-and-trade systems. They include the atmosphere of the Paris Agreement which stimulates ambitious actions, and the uncertainty for market supply factors like the cap (or policy), emissions and abatement costs. actions. That is, for cap and trade to play a critical role in the Paris Agreement, regulators should deal with both agents' expectations (concerns) for continuously decreasing caps and uncertainties around the supply and the consequent price.

1.4. POLICY IMPLICATIONS

In this section, we discuss policy implications and the alternatives to prevent or reduce unintended consequences caused by endowment effects. We consider both the long-term goal which can be updated with a realized climate damage function and the smoothing transition to ambitious climate actions. For policy implications to be practical and meaningful for most countries which are preparing or initiating the cap and trade under the Paris Agreement, we mainly consider the case of allowance shortages in the next period and participants expect that the future market is uncertain. Since our analysis is based on the forward-looking reference price and agents with compliance obligations, our implications will be more relevant when the allowance price is highly influenced by future market supply, such as when there is a fixed cap and market participants are sensitive to compliance failure. Under such situations with free allocations, there may be highly large potential for market illiquidity, even when there is over-allocation.

Free allocation vs Auction

Allowances are usually allocated to entities for free (free allocation) and through auction. Under certain circumstances, the final outcomes from emissions would be thought to be independent of the initial allocation of allowances (Hahn and Stavins, 2011). In theory, trading in the market would remove inefficiencies caused by initial misallocation. However, as seen in Appendix A.1.5, the compliance demanders' *MWTP*s are likely to depend on other players' *MWTA*s under market supply shortage. Also, if the market supply in the next period is expected to be insufficient or uncertain, then sellers' *MWTA*s can be even higher. In this situation, current allowance prices would be critically affected by sellers' higher *MWTA*s with strong banking demands. That is, under a high proportion of free allocation and expectations for insufficient market supply in the future, sellers' high MWTA can lead to high willingness-to-bank, supply shortage and unintended price hikes in the current period.

On the other hand, if the allowances are allocated to entities through a competitive auction with measures to prevent market power, then compliance demanders can simply participate in the auction and get allowances instead of purchasing them from sellers. That is, through the auction, buyers (specifically compliance demanders) can be free from sellers' higher *MWTA*s. Along with evidence on efficiency improvements of the auction (Burtraw and McCormack, 2017; Goeree et al., 2010), our study supports the notion that the auction will be socially preferable in terms of the cost-effectiveness and the fairness of allowance allocations which would have been undermined under free allocation.

Are temporary additional allocations effective?

Another option to stabilize the allowance price at the current period may be to temporarily allocate additional allowances to firms, drawing from the Market Reserve within the cap. Here, the idea is that the additional allocation may mitigate the endowment effects of participants and thus recover the trade efficiency by stimulating market players to go on the market in the current period. However, sellers' reference prices are directly related to the expectation for market supply in the future rather than the current supply. That is, temporary allocations cannot reduce the effects of the positive K' in equation (1.7) (reference switching effects). Therefore, this measure will not be helpful for stimulating the trade of allowances because it barely affects sellers' reference prices under continuous concerns over supply shortage.

Also, in the case of countries that have the national GHG mitigation target of the uncertain type under the Paris Agreement, the regulator may be tempted to consider this additional free allocation with the total cap modified with the updated national target. However, this option would just contribute to increasing cumulative market emissions throughout the long-term. We denote additionally allocated allowances for free as $A > 0$. Recall the reference point in section 1.2.2 ($r = (S_t^i + S_{t+1}^i)\beta E(p_{t+1})$). Note that the agent will update his reference point by including $A > 0$ ($r^A = (S_t^i + A + S_{t+1}^i)\beta E(p_{t+1})$) when A is given to each agent. This implies that his $X = W - r$ does not change since A is also added to the existing $W_T^i(Ts_t^i)$ and $W_T^i(Tb_t^i)$. The equation forms for $MWTA/P$ of each agent are equivalent to Proposition 1.1.

Further approaches associated with ambitious climate actions

As mentioned earlier, under the Paris Agreement, the regulators should control both concerns of players about ambitious climate actions and uncertainties surrounding the system. To further approaches toward more ambitious climate actions, the following policy mix can be considered. The main ways are to reduce the system uncertainty and to increase market surplus through more mitigation actions.

Long-term cap with safety valve (I):[28] The regulator, facing uncertainty, may prefer to leave a short-term cap rather than a long-term cap. Borenstein et. al. (2019) argue that the likelihood of extreme-price outcomes may not disappear under a long-term cap because of the relatively high uncertainty of BAU emissions. However, with a short-term cap, it is almost impossible to even form the expected price in the future beyond the level of higher variation for βp_{t+1}. This will increase sellers' *MWTAs* for allowances

[28] The safety valve is a hybrid approach to a cap and trade and one of the existing measures to control the volatility or uncertainty for allowance price or mitigation abatement cost. Safety valve puts an upper bound on the costs that firms will face for complying the obligations by offering the option of purchasing additional allowances at a predetermined fee, where the price ceiling implies that under unexpectedly high mitigation cost, the cap-and-trade system transitions to a carbon tax (Aldy and Stavins, 2012).

much more by Proposition 1.3. On the other hand, the long-term cap can play a critical role in stimulating players' price-elastic abatements (Borenstein et. al., 2019) and thus decreasing the long-term social cost. That is, in equation (1.10), the long-term cap can increase the expectation of m_{t+1} and thus contribute to ease concerns on expected endowment effects (V_{t+1}^{endow}). Here, the long-term cap can be continuously updated with a realized climate damage function.

One of the important implications is that the regulator needs to control the positive K' in Proposition 1.2. Note that in Proposition 1.2 the positive K' is caused by the "reference switching effect" driven by the expectation of the players that the compliance demanders in the next period may suffer from obtaining the allowances from the market. This implies that the regulator should give the participants some guarantees that participants can obtain allowances from somewhere even under the shortage of market supply. The expected effect of safety valve is to maintain the certainty of cumulative emissions throughout a long-term period by smoothing allowance prices over time through banking and borrowing (Aldy and Stavins, 2012). Furthermore, as seen in numerical simulations, the safety valve is likely to partially control the problem of the positive K' in Proposition 1.2 under severe, continuous uncertainties (See Figure 1.3 in section 1.2.3).[29]

(I) + measures to avoid excessive banking (or market power): Despite loose cap, the current shortage of market supply or reaching the ceiling price may be mainly due to severe endowment effects or due to dominant market powers of several firms. This can cause controversy over unfairness of the current allocation from players which do not hold sufficient banked allowances; the regulator can face strong resistances from players in a shortage position. As mentioned in the introduction, endowment effects occur when a good's value appears higher to an individual when viewed as something that could be lost or given up than when evaluated as a potential gain (Kahneman, 2003). Therefore, depreciating the value of excessively banked allowances will remove or reduce the effects of the positive K' in Proposition 1.2. In

[29] Given a long-term mitigation goal, note that the regulator should issue fewer allowances (Fell and Morgenstern, 2010) or buy allowances from outside the system after implementing the safety valve (e.g., California cap and trade program).

practice, this can be applied through various types of measures to reduce the total banked quantities in the market, such as holding limit, constrained banking, intertemporal trading ratio and so on.[30]

1.5. CONCLUSION

In the context of the literature that highlights implications of intertemporal no arbitrage conditions and expectations for carbon price formations, we try to explain endowment effects in the trading behaviors in cap and trade and its impacts. Building on Kőszegi and Rabin's reference-dependent model (2006) with forward-looking reference prices, we show that reference price switching under an expectation of market supply shortage and expected price with higher variances can significantly enhance endowment effects of agents. Our study will have implications that although the overall market is in the surplus position at the current period, the volume of trade can decrease due to agents' expectations and consequent endowment effects, thus increasing allowance prices and the social costs for GHG mitigation with excessive banked allowances. In sum, we present that independence property may not be established by endowment effects, with expectations for insufficient market supply and unclear rules for the exhaustion of the market supply. Our paper also provides practical, actionable recommendations at a time when the Paris Agreement is urging ambitious actions, agents' expectations on decreasing total market surplus have the potential to affect the effectiveness of the system, and the political and economic systems are uncertain as in developing countries.

In terms of policy implications, we highlight the need to pay attention to the expectations and concerns related to compliance demand, because if agents feel that the market supply is not large enough, the price elasticity of compliance demands gets lower, thus affecting the expectations of agents holding the extra allowances. Second, the long-term cap with the safety valve would be preferable than the short-term cap. The long-term cap stimulates firms to invest in the abatement technologies, thus decreasing the uncertainties

[30] These sorts of measures are different from fully restricted banking where the banking itself is not allowed. That is, these measures are intended to prevent excessive banking, not to discard merits of banking (Rubin, 1996; Schennach, 2000) that allows firms to shift abatement in an intertemporal cost-effective manner and to hedge against allowance price risk related to uncertain mitigation costs, uncertain emissions, and other stochastic elements.

for the “effective market supply”. Next, an auction allocation method may be socially preferable because allowance prices in official auctions are not influenced by sellers’ *MWTAs*. When agents’ endowment effects are present, additional free allocation of allowances (perhaps arising from uncertain national GHG targets under the Paris Agreement), would just increase total cumulative emissions without addressing endowment effects. Lastly, for excessively banked allowances under free allocations, we recommend the practice of depreciating their values; this practice is currently used for addressing over allocation and oversupply problem.

Furthermore, our paper presents the implications on the market analysis framework. Most studies have applied the cost-effectiveness or efficiency framework as an analytical tool for the market analysis in the long-term, which depends on the marginal damage of emissions or marginal abatement cost, given the efficiency of the transaction. According to the cost-effective framework, the allowance prices would be equivalent to the marginal abatement cost. However, our paper indicates that the endowment effects and consequently reduced transactions in the market can lead to a disparity between allowance prices and abatement costs without nudging or correcting the system; this implies that in this situation, our supply/demand framework for allowances can be more appropriate.

Our study comprehensively and theoretically explains endowment effects and its implications, and thus will provide strong insights and guidance for further specific research. First, this paper covers a wide range of issues; further specific research could be more intensively, elaborately focused on the sub-topics with empirical studies. Although there were existing studies to test the existence of endowment effects, they were based on specific cases or scenarios, and cannot answer the question of why. This paper will provide the better understanding of existing studies and will be the basis of more improved future research. Second, our paper focuses just on the trading behavior. If we consider the abatement efforts along with the trading behavior, we can induce more plentiful implications on achieving long-term goals. There are also other considerable behavioral preferences such as probability weighting, time-inconsistent preferences, or hyperbolic discounting.

As for policy options, serious impacts from endowment effects may be due to the small market size or the small number of players. Therefore, global linking among cap-and-trade systems or the participation in the international carbon market may be good approach to reduce the overall abatement costs, given the fairness of burden-sharing and political feasibility. Lastly, the regulator should control the variation of the expected price at the targeted time caused by uncertainty of future emissions. In our views, this uncertainty should be likely to be addressed with the greater availability of cost-effective abatement technologies and more price-elastic supply of emission abatement outcomes under the long-term cap rather than the short-term cap fitted to fluctuated emissions.

(a) the effect of η_s (b) the effect of λ

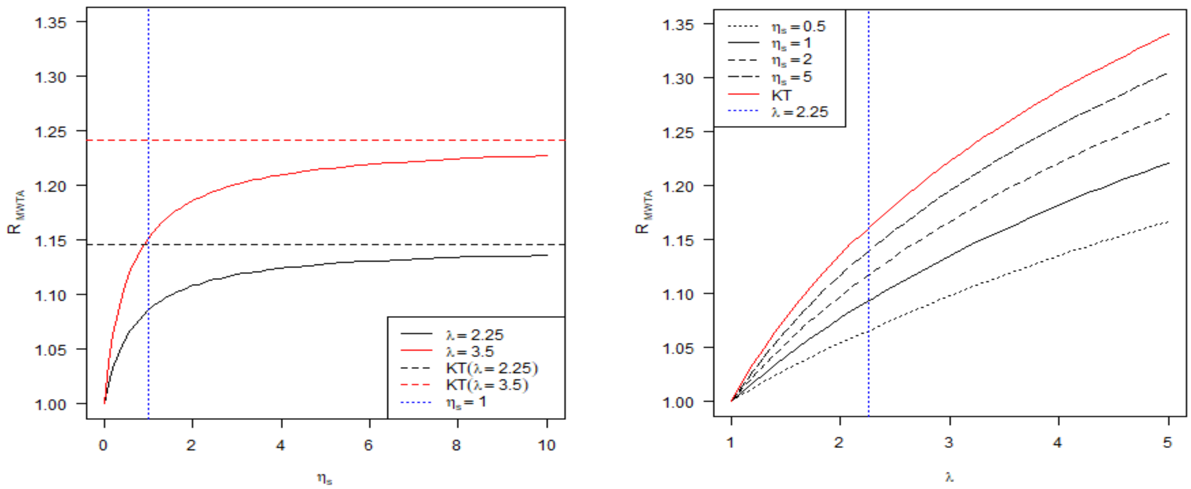

Figure 1.1. The effect of loss aversion and reference dependence on the relative MWTA

Note: λ and η_s are the parameter of loss-aversion and reference dependence, respectively. "KT" indicates a Kahneman-Tversky functional form ($\eta_s = +\infty$))

(a) the effect of c (b) the effect of σ_ε (Std of $log \frac{\beta p_{t+1}}{\beta E(p_{t+1})}$)

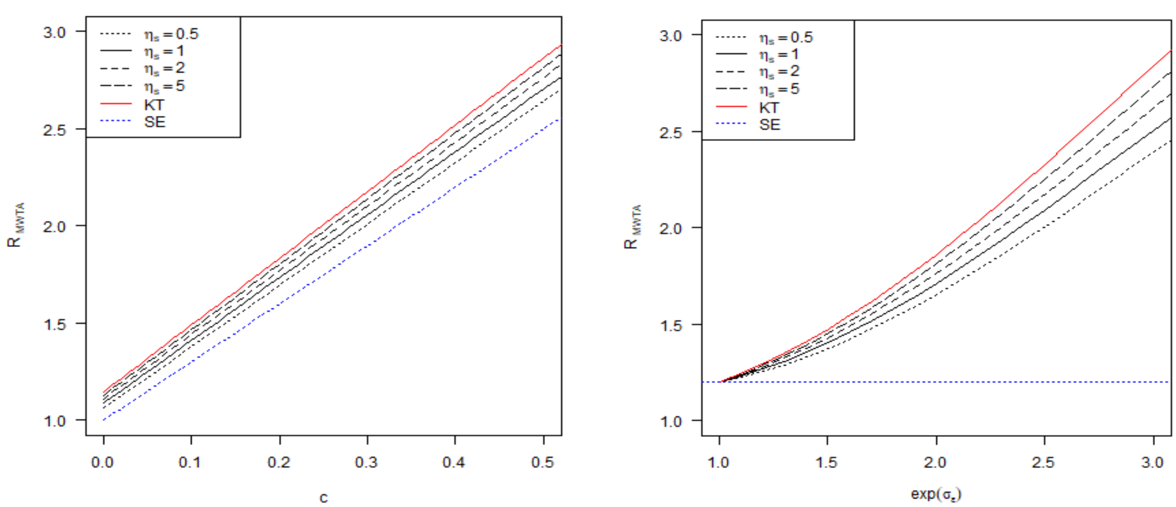

Figure 1.2. The effect of reference switching and higher variance on the relative MWTA

Note: c is the probability for the shortage of market supply in the future period. "KT" indicates a Kahneman-Tversky functional form ($\eta_s = +\infty$) and "SE" indicates a reference price switching effect. $\lambda = 2.25$. $log\, \beta p_{t+1}/\beta E(p_{t+1}) \sim N(0, 0.20)$ is assumed in Figure 1.2(a), and $c = C(S_{t+1} < \bar{S}_{t+1}) = 0.1$ is assumed in Figure 1.2(b).

(a) the effect of c (b) the effect of σ_ε (Std of $log\,\frac{\beta p_{t+1}}{\beta E(p_{t+1})}$)

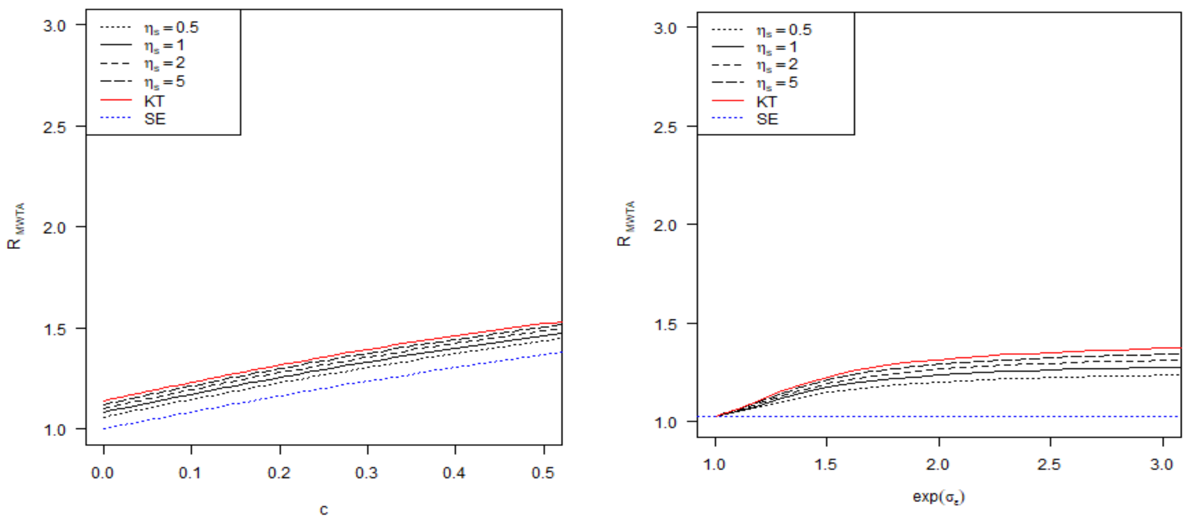

Figure 1.3. The effect of the safety valve on the relative MWTA

Note: c is the probability for the shortage of market supply in the future period. "KT" indicates a Kahneman-Tversky functional form ($\eta = +\infty$) and "SE" indicates a reference price switching effect. $\lambda = 2.25$. $log\,\beta p_{t+1}/\beta E(p_{t+1}) \sim N(0,0.20)$ is assumed in Figure 1.3(a), and $c = C(S_{t+1} < \bar{S}_{t+1}) = 0.1$ is assumed in Figure 1.3(b). In the price collar as a safety valve, the ceiling price ceiling and flooring price are assumed to be censored at the level of $R_{MWTA} = 2$ and $R_{MWTA} = 0.5$, respectively

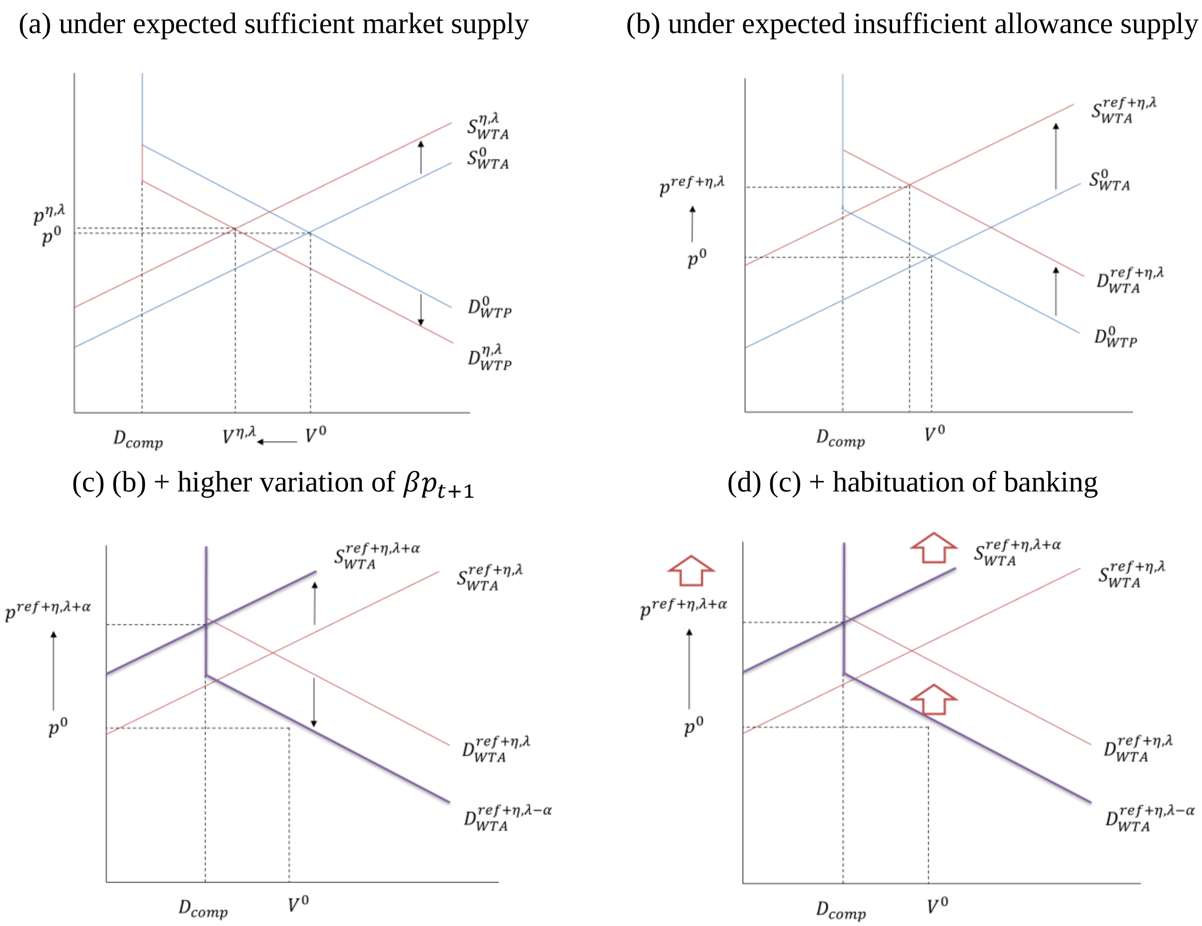

Figure 1.4. The supply/demand curve for the allowance with gain-loss utility

CHAPTER 2

THE CARBON PRICE MOVEMENTS UNDER THE EXPECTATION FOR INSUFFICIENT MARKET SUPPLY: THE CASE OF THE KOREAN EMISSION TRADING SCHEME

2.1. INTRODUCTION

The cap-and-trade system has become a widely used policy instrument for controlling pollutants generating negative externalities based on the premise that efficient trading of allowances will minimize the overall abatement costs. The trading system stimulates firms with low abatement costs for reducing the emissions to sell their unused, spare allowances to the market, which, in turn, enables firms with high abatement costs to buy allowances from the market. Hence, the cap-and-trade system is now becoming one of the major options to implement even nationally determined contributions (NDC) under the Paris Agreement.

Recently, inefficient trading and consequent market liquidity problems, where firms choose not to sell allowances to bank them for their own future use, have been reported around several cap-and-trade systems that are prepared for the implementation of the Paris Agreement (Asian Development Bank, 2016; 2018). The tendency to prefer holding allowances to selling them can be explained by several reasons like transaction costs (Stavins, 1995), risk-averse attitudes under uncertainties such as seller's less abatement and less allowance supply (Ben-David et al., 2000), less trading (Baldursson and von der Fehr, 2004), outcomes of intertemporal portfolio management for compliance (Rousse and Sévi, 2007), and non-cost-minimizing behaviors (e.g., endowment effects or status quo) (Hahn and Stavins, 2013). However, our paper focuses on firms' expectations (or concerns) for the shortage of market supply in the future, noting that with the uncertainty caused by policy and firms' behaviors, such expectations can significantly increase current allowance prices.

There is also a vast number of empirical studies investigating characteristics and drivers of allowance prices (Friedrich et. al, 2020). Several studies recently emphasized the importance of firms' expectations in the formation of allowance prices, especially in cap-and-trade programs that allow intertemporal trading with banking. As firms minimize the cost of their abatements over time, the opportunity to carry over allowances into the next period implies an arbitrage condition between the current price and the expected price in the next period (Borenstein et al., 2019; Aldy and Armitage, 2020). That is, if an allowance surplus exists in the market, the current allowance price can be significantly influenced by firms' expectations of the prices in the future (Lintunen and Kuusela, 2018; Kuusela and Lintunen, 2020; Quemin and Trotignon, 2021). In the presence of policy uncertainties, firms' expectations regarding the future state can even a larger role in determining the current price (Koch et al., 2016; Pizer and Prest, 2020).

The expectation of insufficient market supply can occur due to unexpected demand shocks under an inflexible cap. Especially under the Paris Agreement, which is urging ambitious actions by the global community, firms in the cap-and-trade are prone to continuously decreasing caps in the future along with policy uncertainties. Therefore, when the cap is constant or inflexible to adjust, firms' expectations of shortage in market allowance supply can dramatically increase banking demand in the current period, leading to sharp increases in both allowance prices and compliance costs. Such phenomena can cause illiquidity in the market accompanied with an increase in social costs of greenhouse gas (GHG) abatements and unintended interventions of the regulator to resolve market distortions.

The Korean Emission Trading Scheme (K-ETS), the second-largest nation-wide cap-and-trade system in the world, represents a good example. The K-ETS, which plays a crucial role in the implementation of the NDC under the Paris Agreement to reduce the national emissions by 24.4% from 2017 to 2030, is experiencing participants' high banking demands (Asian Development Bank, 2018). Here, firms pose the expectation of insufficient market supply under the inflexible short-term cap and choose to bank, rather than trading, their free-allocated allowances into the next year.[31] This leads to liquidity problems, and therefore, to significantly increased prices.

We build on the recent theoretical work of Kuusela and Lintunen (2020) and Quemin and Trotignon (2021) on the role of firms' expectations in the allowance price formulation and empirically investigate how allowance prices move under the expectation of insufficient supply. Our study period reflects markets under the following situations: an inflexible cap with high proportions of free allocation, policy uncertainties in the long-term, and market participation limited to only obligated firms. We compare allowance price movements to a random walk process under the weak-form market efficiency (Fama, 1965) as a reference, considering that the future price under the expected supply shortage is extremely uncertain. For resolving illiquidity problems and price hikes, the K-ETS eventually intervened by implementing a constrained banking rule for each firm, with the goal of increasing trading activity and stabilizing allowance prices. Here, our analysis includes the price movements after the announcement of individually constrained banking schedules. Also, some may argue that unintended price movements in K-ETS may be due to shocks from other markets such as an international oil price and a composite stock price index (e.g., Korean Composite Stock Price Index), which are strongly involved with the Korean economy and may influence allowance demands. We investigate potential spillover effects to determine whether allowance price movements are critically influenced by the international oil and the Korean stock market. Lastly, we present that if specific price levels are not predetermined when the shortage of market supply occurs, it causes firms' expectations to be highly variable, which can be made worse by a short-term cap (uncertain long-term policy) and a high proportion of free allocations (firms' uncertain holding tendency). We explore policy options that can be harmonized with individually constrained banking in the K-ETS.

Our study contributes to the literature by empirically supporting the notion that firms' expectations play a critical role in the allowance price formation. Second, the K-ETS has been overlooked in the literature

[31] The reason we use the term "inflexible" rather than "fixed" is that there is a direct provision for the cap adjustment in the law. However, the adjustment is made only under certain conditions and requires additional administrative costs and procedures including public hearings. That is, the K-ETS's cap is almost fixed and can provide implications on a fixed cap.

despite its size, high stringency, and the potential to provide important lessons for developing countries. In the context of the Paris Agreement, our study on the K-ETS provides valuable implications on why and how to control both firms' continuous expectations of insufficient market supply and uncertainties surrounding high variations in prices. There is also extensive literature on the high abatement cost shocks (or price spikes) and policy options in cap-and-trade (Holt and Shobe, 2016; Salant, 2016; Fell, 2016). However, to the best of our knowledge, there is no study that covers both the excessive banking issue and price hikes, including the effects of individually constrained banking as a market stability measure. Noting that the constrained banking should be supported by a policy, we explore possible policy options such as flexible supply with long-term cap and increases in auction allocations.

The structure of our study is as follows. Section 2.2 overviews the operations in the K-ETS and the theoretical background of the allowance price formulation under the expectation of insufficient market supply. Section 2.3 illustrates the methodologies and data used in this study and section 2.4 shows the empirical results. Section 2.5 discusses the main causes of unintended price movements and policy implications and concludes this paper.

2.2. THE K-ETS'S OPERATION AND THEORETICAL BACKGROUND

2.2.1. The overview of the K-ETS's operation and allowance prices

The K-ETS is the second-largest carbon market at the country level and the first nationwide mandatory ETS in East Asia (ICAP, 2020). The system was launched in early 2015 to play a crucial role in achieving the NDC target of 37% below 2030 business as usual (BAU) emissions under the Paris Agreement and accounts for about 70-73% of the national GHG emissions with about 500-600 firms. The trading period is three years (the first phase 2015-2017 and the second phase 2018-2020), while the compliance cycle is based on one year.[32] After one year of emission activities, firms are required to submit their verified emission reports until the end of March (report deadline) and to surrender allowances equivalent to their

[32] Starting with the third phase, the trading period became five years (2021-2025).

emissions for compliance obligations until the end of June (surrender deadline).[33] If firms fail to satisfy their obligations, they need to pay a penalty, which is the minimum value of three times the average allowance price and KW 100 thousand (about US$ 86) per ton. Unlimited banking was originally applied both within the phase and between phases.

If there is no specific reason, the cap is fixed during a phase, and a limited amount of Market Reserve is distributed to the firms under the restricted conditions. When the market supply including the Market Reserve is exhausted, specific rules for market stabilization are not clear.[34] Allowances are mainly distributed through free allocation. The proportions of free allocation are 100% in the first phase and 97% (3% auction) in the second phase. For both phases, just firms with compliance obligations can participate in the allowance trading, and only spot transactions are allowed. However, in the third phase (2021-2025), participation of the third parties such as individuals is also permitted and derivatives like futures contracts are planned to be introduced.

The K-ETS is currently suffering from supply-demand imbalance (higher demand) and policy uncertainties with the expectation of insufficient market supply in the future (Asian Development Bank, 2018). The survey from the Ministry of Environment in the Republic of Korea (MOE, 2020a, 2020b) shows the tendencies of firms not to trade allowances for speculative purposes.[35] 91.7% of responding firms (211 out of 230 firms) stated that the minimization of emission trading (through just buying for compliance obligations and banking) is more preferred to the profit maximization from trading, and 82.6% (190 out of 230 firms) said that the allowance would rise in the future and 53.7% of those (102 out of 190 firms) expressed that the shortage of market supply would cause this increase in the allowance price.[36] Firms face uncertainties of market supply in the future, especially beyond the year 2020, expecting that the total allowances in the market will continuously decrease due to the implementation of the Paris Agreement. Hence, although the market had some level of surplus, sellers unexpectedly tried to bank more allowances

[33] After individually constrained banking, the deadlines have been postponed to August or September.
[34] We discuss this issue in detail in section 2.5.
[35] The response rate was 42.5% (230 of a total of 541 firms participated in both the first and second phases).
[36] This result is consistent with the results of the survey in Suk et al. (2018).

into the next period, and thus the allowance price increased rapidly every time the surrendering time comes (MOE, 2019, 2020a, 2020b).

Figure 2.1 demonstrates Korea Allowance Unit (KAU) prices over time. Two features on K-ETS emerge. First, the K-ETS is one of the systems which have marked the highest carbon price in the world. The allowance price started from $10/ton in early 2015 but tripled in early 2020. Second, price hikes seem to be periodic between the year end and the surrender deadline, with spikes occurring as the surrender deadline approaches. These are likely because current compliance firms were unable to buy allowances from the market due to other firms' tendencies to hold allowances and wait.

As a result, the government intervened in the market, taking several measures to stabilize the allowance price and to prevent excessive banking throughout both phases. For the first phase, i) "auction allocation" from the Market Reserve in the compliance cycle for the first year and ii) "individually constrained banking" to entities in the compliance cycle for the second and third year were implemented. In particular, individually constrained banking seemed to be effective in increasing the volume of allowance trading and stabilized the price in the first phase. Therefore, in the middle of the second phase, iii) "individually constrained banking" was systemized for both within the phase and between phases.[37] The KAU price, however, kept increasing even after the announcement of constrained banking until the COVID-19 pandemic.

2.2.2. Theoretical background

<u>The allowance price and the expectation of insufficient market supply</u>

For the formulation of allowance price, we build on the theoretical frameworks of Kuusela and Lintunen (2020) and Quemin and Trotignon (2021). For the policy effectiveness in cap-and-trade, the regulator requires each firm to surrender allowances at the end of each compliance cycle and imposes a penalty on compliance failure much larger than the benefit. This leads firms to have compliance demand

[37] The banking is constrained to the maximum of two limits: a) two or three times the annual amount of net selling, and b) the fixed quantitative limit (e.g., xxxx KAUs). According to this rule, the more selling, the more the firm can bank allowances to the next period.

for allowances equivalent to their emission levels. Let the subscript C denote the "current period" under the time frame of "implementation period" and the subscript t the "current time" under the daily time frame.[38] The representative firm's compliance demand (that is, the emission level) in period C, q_C, satisfies the following first-order condition of the firm's maximization problem $\max_{q_C} B(q_C) - p_C q_C$:

$$p_C = MB(q_C) = MC(m_C), \tag{2.1}$$

where p_C is the prevailing allowance price in the current period C, $MB(\cdot)$ is a marginal benefit function for emissions, and $MC(\cdot)$ is a marginal abatement cost function. Here, since $B(\cdot)$ also implies a benefit function for avoided abatements, $MB(q_C)$ is also equal to $MC(m_C)$, where $m_C = \hat{q}_C - q_C$ is the realized abatement level, and $\hat{q}_C$ is the realized baseline emission level in period C.

Additionally, the regulator generally operates the cap-and-trade system with the banking rule in terms of intertemporal efficiency.[39] If the firm minimizes the cost over time, the banking demand in period C, b_C, satisfies the following intertemporal arbitrage condition:

$$b_C \geq 0 \quad \text{and} \quad p_C - \beta E_C(p_{C+1}) \geq 0, \tag{2.2}$$

where $\beta = (1+r)^{-1}$ is the discount factor and r is the discount rate. If the present value of the expected price for period $C+1$ is higher than the current price (i.e., $\beta E_C(p_{C+1}) > p_C$), banking is profitable and therefore leads firms to carry over allowances into the next period $C+1$, potentially increasing the current allowance price.

Figure 2.2(a) illustrates how the allowance price can be formulated through the marginal abatement cost $MC(m_C)$ and firm's expectation. When the current cap Q_C is binding (i.e. $S_C = Q_C - q_C + b_{C-1} = 0$ where S_C is the market allowance supply in period C), the current allowance price is determined by equation (2.1), $p_C = MC(m_C)$. If firms hold spare allowances more than their compliance demand ($S_C > 0$), then

[38] Here, the "implementation period" can mean both one year and the phase (three years) in the K-ETS. Based on these notations, the "current period" and "next period" are denoted as the subscript C and $C+1$, respectively. Likewise, the "current time" and "next time" are denoted as the subscript t and $t+1$, respectively.

[39] For simplicity, we assume that the borrowing from the next period is not allowed.

equation (2.2), $p_C = \beta E_C(p_{C+1})$, determines the allowance price. Combining both conditions lead to the following market equilibrium price in a dynamic setting (Kuusela and Lintunen, 2020; Quemin and Trotignon, 2021):

$$p_C(S_C) = \max\{\beta E_C(p_{C+1}|I(S_{C+1})),\ MC(m_C)\}, \tag{2.3}$$

where $I(\cdot)$ is the information set in period C. That is, on cap-and-trade with unlimited banking, if firms have a surplus of allowances in period C, the current allowance price p_C is significantly influenced by the expected market supply and thus, by the expected price for period $C+1$. In particular, when the regulator tries to set an ambitious long-term goal, he might plan a lenient cap in the initial phase and make the caps stricter phase by phase. However, equation (2.3) implies that if firms' discounted expected price for period $C+1$, $\beta E_C(p_{C+1}|I(S_{C+1}))$, is high, the current price can increase to $\beta E_C(p_{C+1}|I(S_{C+1}))$ despite the low marginal abatement cost, $MC(m_T)$.

Next consider what happens if firms expect emissions to exceed the cap level in period $C+1$ so that a negative market supply occurs ($S_{C+1} = Q_{C+1} - q_{C+1} + b_C < 0$).[40] Firms will additionally consider the possibility of the shortage of market supply and the resulting expected price. Assume that the expected prices under $S_{C+1} < 0$ and $S_{C+1} \geq 0$ are $\bar{p}_{C+1}$ and p^a_{C+1}, respectively. Here, $\bar{p}_{C+1}$ can be the expected price under market stability measures or even the penalty level for compliance failure as the worst case. Then, following Yoon et al. (2021), the payoff to holding an allowance in period $C+1$ will be:

$$E_C(p_{C+1}) = (1-g)\cdot p^a_{C+1} + g\cdot \bar{p}_{C+1}, \quad g = G(S_{C+1} < 0), \tag{2.4}$$

where $G(\cdot)$ is the cumulative distribution function of S_{C+1} and g is the probability that there is a shortage of the market supply in period $C+1$. That is, when firms expect a shortage of market supply in the future ($S_{C+1} < 0$), the expected price or compliance cost for the future can significantly increase, depending on

[40] This situation is quite possible because of the uncertainty of market emissions, even though the regulator sets the cap for the next period based on the best available information and data. Such expectation can also be explained in the context of the information asymmetry: the regulator often has more resources to estimate marginal costs and benefits, while individual firms know just their own costs for the abatement and may feel that the cap would be too strict.

the probability of the shortage, g, and the expected price or compliance cost level $\bar{p}_{C+1}$. Then, equation (2.3) can be modified as follows:

$$p_C(S_C) = \max\{\,\beta E_C(p_{C+1}|I(S_{C+1}, g, p^a_{C+1}, \bar{p}_{C+1})),\ MC(m_C)\}. \tag{2.5}$$

When the constrained banking for each firm is scheduled at the end of the compliance cycle, each firm's banking b^i_C has an upper limit of $\bar{b}^i_C$. Then, they will try to sell the remaining allowances beyond $\bar{b}^i_C$ in period C under the expectation of insufficient market supply. This option may be effective in preventing excessive banking by firms and thus increasing the market supply for period C. We will discuss the implications of constrained banking in more detail in section 2.5 along with empirical results.

The allowance price and the random walk process

We analyze whether the allowance price in K-ETS follows a random walk process, comparable with the efficient market hypothesis (EMH). Fama (1965) argues that the market price fully reflects all available information at any time and divides the markets into three categories: i) a strong-form efficient market, ii) a semi-strong-form efficient market, and iii) a weak-form efficient market.[41] Our study focuses on whether the allowance market is weak-form efficient, where the price fully reflects all available historical information making it impossible to predict future prices.

In a weak-form efficient market, as new information occurs in an unpredictable manner, the asset price should also fluctuate randomly. This randomness and independent, identically distributed successive prices or returns are the basis of a weak-form efficient market (Fama, 1970). This can be most easily represented in the following geometric random walk process with a drift R:

$$ln\ p_{t+1} = R + ln\ p_t + e_{t+1}, \tag{2.6}$$

[41] In a strong-form efficient market, the asset price can sufficiently reflect historical, public, and internal information. Also, EMH has been tested for the EU-ETS allowance market in previous studies. Daskalakis and Markellos (2008), for example, rejected the weak-form efficiency hypothesis in the first phase (2005-2007). Montagnoli and de Veries (2010) also rejected the weak-form efficiency for the first phase (2005-2007) and argued that EMH partially holds for the first implementation year of the second phase (2008-2012). Yang et al. (2018) find that only the second phase supports weak-form efficiency while the first and third (2013-2017) phases do not.

where p_t is the price in the current time, and e_{t+1} is an independent and identically distributed (i.i.d.) error term with zero mean and constant variance σ^2. However, the i.i.d. assumption is too strong. Therefore, as in other empirical studies, we relax this assumption with the martingale difference sequence (m.d.s. assumption) where e_{t+1} does not satisfy the i.i.d. assumption, but it is serially uncorrelated and $E(e_{t+1}|e_t, e_{t-1}, \cdots) = 0$ for any t.[42] Denote $\frac{1}{R+1} = \beta_d$, which is the daily discount factor, $l\,n(p_{t+1}/p_t) \simeq \frac{p_{t+1}-p_t}{p_t}$ and take the expectation of both sides to obtain:

$$\beta_d E_t(p_{t+1}) = p_t. \quad (2.7)$$

That is, the best prediction of the price in time $t+1$ is the current price p_t, reflecting all available information for the expectation of time $t+1$.

Note that under the expectation of market supply shortage, equation (2.5) also implies that the additional information such as g and $\bar{p}_{T+1}$ should be anticipated prior to expectations of future prices. The problem is that the information on these additional factors can be extremely uncertain, which will cause higher variation and larger errors in firms' expectations. These would make firms wait for more (accurate) information instead of trading, which may cause serial correlations among price returns. Higher variation and larger errors in expectations can also cause extreme volatility in the process of correcting errors or updating the information set (Figure 2.2(b)). That is, under the expectation of insufficient market supply, it is unlikely that the current price p_t is the best prediction of the future price.

2.3. METHODOLOGY AND DATA

2.3.1. The variance ratio tests

We test whether KAU price returns support the weak-form efficient market hypothesis based on a random walk process (especially, the m.d.s. assumption). Tests of the m.d.s. assumption have been implemented in finance and economics studies for market efficiency and rational expectations, and several

[42] This model corresponds to the Random Walk 3 model in Cambell et al. (1997).

variance ratio (VR) tests are widely used to empirically test for the m.d.s. assumption. We use in our study the wild bootstrap automatic VR (WB-AVR) test of Kim (2009). This test is an improved version of the VR test (Lo and MacKinlay, 1988), and robust to conditional heteroskedasticity which is a typical feature of stock returns (Charles et al., 2011).

The idea of the VR test is that the variance of random walk increments is linear in the time interval. That is, under a random walk, the variance of k-period return $y_k = \ln p_t - \ln p_k$ is k times the variance of one-period return $y_t = \ln p_t - \ln p_{t-1}$. The variance ratio of the k-period return can be defined as:

$$\widehat{VR}(k) = \frac{var(y_t + y_{t-1} + \cdots + y_{t-k+1})/k}{var(y_t)} = 1 + 2\sum_{i=1}^{k-1} \frac{(k-i)}{k}\hat{\rho}_i \tag{2.8}$$

where $\hat{\rho}_i$ is the sample estimate of the autocorrelation coefficient for the i^{th} lag of y_t. That is, $\widehat{VR}(k)$ is a linear combination of the autocorrelation coefficients with linearly decaying weights; thus, we can think of the VR test as a test of autocorrelation in returns.[43] To avoid an arbitrary choice of k, Choi (1999) proposes the automatic variance ratio (AVR) test using a fully data-dependent method building on Andrews (1999) and presents the standardized statistic as $AVR(k) = \frac{\widehat{VR}(k)-1}{(2)^{1/2}(T/k)^{-1/2}}$. To improve the AVR test under the small sample and conditional heteroskedasticity, Kim (2009) proposes the WB-AVR test, which is conducted in three steps as follows:

1. Form a bootstrap sample of size T as $y_t^* = \eta_t y_t$ $(t = 1, \ldots, T)$, where η_t is a random variable with zero mean and unit variance;

[43] Since the variance ratio test aims to detect autocorrelations in returns, the portmanteau test (Ljung and Box, 1978) is also widely used for testing the martingale property. The portmanteau test adds up the squared autocorrelations, while VR tests add up the autocorrelations themselves. As mentioned in Liu and He (1991), if returns exhibit small autocorrelations with the same signs of their lags, the portmanteau test does not reject the m.d.s. hypothesis. Also, the automatic portmanteau test (Escanciano and Lobato, 2009), which is an improved version of the conventional portmanteau test, is robust to non-normality and conditional heteroskedasticity; however, Charles et al. (2011) argue that in a small sample, the WB-AVR test has higher power than the automatic portmanteau test. Therefore, we use the WB-AVR test in our main analysis.

2. Calculate $AVR^*(k^*)$, which is the $AVR(k^*)$ statistic calculated from $\{y_t^*\}_{t=1}^{T}$;

3. Repeat 1 and 2 B times to produce the bootstrap distribution of the AVR statistic $\{AVR^*(k^*; j)\}_{j=1}^{B}$.

For the random variable η_t, we use the two-point distribution proposed by Mammen (1993) as in Escanciano and Velasco (2006), and Charles et al. (2011, 2017). The number of bootstrap replications is set to 10,000 and the bootstrap confidence interval is calculated based on the two-tailed test.

Wright (2000)'s sign test also detects the martingale property, reducing size distortions by using an exact sampling distribution and presenting more exact statistic under the conditional heteroskedasticity. Denote $z_t = 2u(y_t, 0)$, where $u(y_t, 0) = 1(y_t > 0) - 0.5$. If the return y_t satisfies the m.d.s. assumption, then z_t, which takes the value of 1 or -1 with the same probability, is i.i.d. with zero sample mean and variance of one. With the null hypothesis of $\widehat{VR}(k) = 1$, the test statistic can be defined as:

$$Z_1(k) = \left(\frac{\frac{1}{Tk}\sum_{t=k+1}^{T}(z_t + z_{t-1} + \cdots + z_{t-k})^2}{\frac{1}{T}\sum_{t=1}^{T} {z_t}^2} - 1\right) \cdot \left(\frac{2(2k-1)(k-1)}{3kT}\right)^{-1/2} . \tag{2.9}$$

Since this test uses the sign instead of the magnitude of y_t in equation (2.8), $Z_1(k)$ is independent of the conditional standard deviation and so, robust to conditional heteroskedasticity. The null hypothesis in the individual sign test is also applied to every $k > 1$. Hence, the joint statistic for multiple ks, following Kim (2006) and similar to the statistic in Chow and Denning (1993), can be established as follows:

$$JZ_1 = max\{|Z_1(k_i)|\}_{i=1}^{n} \text{ for } i = 1, \cdots n. \tag{2.10}$$

where n is the number of the chosen ks. We obtain critical values for the joint test statistic through the distribution of JZ_1^*s (following Kim and Shamsuddin, 2008), which is attained through 10,000 replications of $\{Z_1(k_i)\}_{i=1}^{n}$.

2.3.2. Detrended fluctuation analysis and fractal dimension

In addition to autocorrelations in the short-term, there are properties that depart from the random walk process: long-range dependence and local dependence. Under the random walk hypothesis, a time series has no long-range dependence, no local dependence, and no (local) anti-correlations (Hurst, 1951; Kristoufek and Vosvrda, 2014; Tarnopolski, 2016; David et al., 2020). To further understand the results of the section 2.3.1 analysis, we investigate the memory property in time series of KAU returns or price levels. Since the K-ETS has experienced important several events as mentioned in section 2.2.1 and undetectable breakpoints even within a sub-sample period may exist due to local liquidity problems, it is also important to investigate how the long-range dependence changes over time and whether there are local trends.

Long-term memory (long-range dependence) in time series (specifically, price returns) has often been described by the H exponent (Cizeau et al., 1997; Ausloos et al., 1999). Since the importance of long-term memory in asset markets was first studied by Mandelbrot (1972), the H exponent has been calculated by several algorithms like classical rescaled range (Mandelbrot, 1972), wavelet decomposition (Simonsen et al., 1998), and Fourier analysis (Roerink et al., 2000). In particular, the detrended fluctuation analysis (DFA) proposed by Peng et al. (1994) has been widely used for calculating the H. It has been also used to investigate market efficiencies for emission allowance (Zheng et al., 2015), foreign exchange (Abounoori et al., 2012), crude oil (Alvarez-Ramirez et al., 2008; Alvarez-Ramirez et al., 2010; Wang and Liu, 2010; Wang et al., 2011), metal, energies, and soft commodities (Kristoufek and Vosvrda, 2014), ethanol and gasoline (David et al., 2020), and agricultural commodities (Kim et al., 2011).

The DFA uses the correlation structure of market returns' fluctuations at different time scales, compared to those of random walk process; here, the H can simply be calculated by the slope based on points associating $log(F(j))$ with $log(j)$ where j is the length (j observations) of segments divided from the whole data and $F(j)$ is the fluctuation function at j. Along with its simplicity, it can also avoid spurious correlation or self-similarity (David et al., 2020). Therefore, in this paper, we use the DFA to obtain the H. Hurst exponent H, where $0 < H < 1$, can be characterized as follows (Hurst, 1951; Tarnopolski, 2016; David et al, 2020): i) when $H = 0.5$, the returns have no long-term memory (random walk process), ii) when $H > 0.5$, the returns have long-term memory (persistent process), and iii) when $H < 0.5$, the returns have short-term memory (anti-persistent process). Detailed procedures to calculate the H can be seen in Appendix B.1.1.

Local memory based on the roughness of the series (KAU price levels in our analysis) can be measured by the fractal dimension D in a fractal dimension (FD) study. Since specific parts of the series can have different properties from the whole sample, the series can be locally correlated (locally trended) even though they have long-term memory globally. Since Kristoufek and Vosvrda (2014) introduce the relationship between the market efficiency in stock indices and the FD, the FD has been used to test market efficiencies for metal, energies, soft commodities (Kristoufek and Vosvrda, 2014), ethanol, and gasoline (David et al., 2020).

The D value provides the information about how much space fills the time series. The fractal dimension D, with $1 < D \leq 2$, can be summarized as follows (Kristoufek, 2013; Kristoufek & Vosvrda, 2014): i) when $D = 1.5$, the series have no local memory (random walk process), ii) when $D > 1.5$, the series have local short-term memory (anti-persistent process), and iii) when $D < 1.5$, the series have local long-term memory (persistent process). The more fluctuations of the series, the higher D value in the space. As in Kristoufek and Vosvrda (2014) and David et al. (2020), we use the Hall-Wood estimator $\widehat{D}_{HW}$ (Hall and Wood, 1993) to obtain the D value.[44] Appendix B.1.2. provides detailed explanations for $\widehat{D}_{HW}$.

2.3.3. Spillovers from other markets

Previous studies on the fundamentals of allowance prices generally consider allowance market variables, energy market variables, weather variables, and variables related to cap-and-trade systems or rules. To see if other markets' factors lead to abnormal movements in allowance prices, we identify the time-varying relationships between allowance prices and domestic economic activities measured by the

[44] In their studies, the robust Genton estimator (Genton, 1998) is also used. However, the robust Genton estimator breaks down frequently due to the ubiquitous discreteness of real-world data (Gneiting et al., 2012). Our failure of obtaining the estimates might be due to the discreteness of our data. See Gneiting et al. (2012) for statistical properties of several estimators of the fractal dimension D, including Hall-Wood and robust Genton estimator.

international oil prices (Dubai oil price) and a stock index (Kospi200 index) throughout both phases in the K-ETS.[45]

To consider the spillovers from other assets and higher order of lags, we also use the modified generalized forecast error variance decomposition (GFEVD) (Lanne and Nyberg, 2016) based on the VAR(p) model.[46] Following Diebold and Yilmaz (2014) and Tan et al. (2020), spillovers based on GFEVD can be captured by five components (see the details in Appendix B.1.3). In this paper, we focus on "total" and "from" spillover indices to determine the effects of other markets on allowance prices. Here, "total" spillover measures the contribution of the information (or shocks) from all assets to the forecast error variance of all assets, the "from" spillover exhibits the contribution of the shocks in other markets to the forecast error variance of one asset.

2.3.4. Data and sub-sample periods

We collect daily data on the KAU spot price from Korea Exchange (KRX) ETS Market Information Platform, the KOSPI Index from KRX, and the Dubai oil spot price from Korea National Oil Corporation (KNOC) Opinet.[47] The sample period is from October 7, 2015 to May 4, 2020.[48] This period reflects markets with the following properties: an inflexible cap with high proportions of free allocation, policy uncertainties in the long-term, and market participation limited to only obligated firms in the K-ETS. All

[45] There are several studies showing empirical evidence of a relationship among the allowance prices in EU ETS, oil prices, and the stock index. For example, Rickels et al. (2014) find a positive effect of the oil price and the stock index. Lutz et al. (2013) show that oil prices and the stock index has significant effects on the allowance price. Creti et al. (2012) find a clear cointegrating relationship in the second phase (2008-2012) with positive and significant effects for oil prices and the stock index, while they find a negative effect of the stock index in the first phase (2005-2007).

[46] The GFEVD can correct the drawback of the well-known DY spillover index proposed by Diebold and Yilmaz (2014) where the relative contributions to the h-period effect of the shocks do not sum to unity.

[47] With local liquidity problems, price movements can rapidly change even within the short term, and the changed price levels do not return to previous price levels easily. Therefore, we focus on daily data rather than weekly or monthly data.

[48] The allowance market opened on January 12, 2015. However, due to the lack of significant transactions and any unexpected noise arising from the introduction stage, allowance price series before October 7, 2015 are excluded from the sample. As for the ending date of the sample, the periods influenced by COVID-19 are also excluded to consider the expectation for insufficient market supply. The cut-off date is selected through the ICSS algorithm of Inchan & Tiao (1994) for the period from the date after KAU17's last trading date to KAU19's last trading date (2018.08.12-2020.09.11).

data series are in the form of natural logarithms and the return of each market is calculated as follows: $y_t = 100 \times (ln\, p_t - ln\, p_{t-1})$. Considering the analysis of spillovers from other markets whether holidays are different among the markets, the data are collected based on the business day of the allowance markets. If a business day in one market is a non-trading day in another, we assign the price in that market to the previous business day's price, which implies zero return on those non-trading days. This approach avoids spurious correlation by maintaining all available data points (Billio and Caporin, 2005). We divide the sample period into six sub-samples based on five important events throughout both phases of K-ETS to investigate the changes in the allowance price dynamics with the policy announcements.

Figure 2.3 shows the changes in the KAU price, the date of each event, and sub-sample periods for the policy effects. The event dates indicate policy announcements after a sharp rise in price or the last day of the compliance cycle for the phase: ① 2016.05.26, announcement of the auction for Reserve for market stability, ② 2017.02.28, informal announcement of individually constrained banking for KAU17, ③ 2017.11.24, formal announcement of individually constrained banking for KAU17, ④ 2018.08.11, the last trading date of KAUs for the first phase, ⑤ 2019.05.15, formal announcement of individually constrained banking for KAU18, KAU19, and KAU 20. Naturally, the "No_Intervention1 (N1)" (2015.10.07-2016.05.26) and "No_Intervention2 (N2)" (2018.08.12-2019.05.15) indicate the sub-sample periods where there is no policy effect, the "Reserve_Auction (RA)" (2016.05.27-2017.02.28) indicates the effects of the announcement of auctioning additional allowances from Reserve for market stability in the first phase, and the "Constrained_Banking1 (CB1)" (2017.03.01-2017.11.24), "Constrained_Banking2 (CB2)" (2017.11.25-2018.08.11), and "Constrained_Banking3 (CB3)" (2019.05.16-2020.05.04) denote the sub-sample periods under the effects of the individual constrained banking. In this paper, Phase 1 indicates the period during which allowance units for the first phase (2015-2017) (KAU15, KAU16, KAU17) were traded (2015.10.07-2018.08.11), and Phase 2 indicates the period from the date after the last trading date of KAUs for Phase 1 to the ending date of the sample period (2018.08.12-2020.05.04).

Table 2.1 shows the descriptive statistics of daily returns of KAU. Except for CB2, the mean of the returns for all periods are more than zero, ranging from -0.150 to 0.457. N1, CB1, and N2 exhibit positive skewness, while RA, CB2, and CB3 display negative skewness. Note that in several sub-periods, returns show both a positive mean and a negative skewness; here we can infer the characteristics of asymmetric volatility. Kurtosis values indicate that returns have leptokurtic and fat-tailed characteristics for all periods. Therefore, the returns in all periods are not normally distributed, which are also supported by highly significant Jarque- Bera (J-B) statistics. Figure 2.4 shows that the return series has heteroskedasticity and the returns in CB2 and CB3 have higher volatility, which is supported by higher standard deviations in CB2 and CB3 compared to the previous period. Finally, all the return series are stationary under the Phillips-Perron (PP) test (1988) with the Newey-West (1987) standard errors, which is robust to serial correlation and general forms of heteroskedasticity, correcting the augmented Dickey-Fuller (ADF) test for unspecified autocorrelation and heteroskedasticity.

2.4. Empirical results

2.4.1. VR tests

In this section, we test the weak-form EMH for daily KAU returns through the variance ratio tests with the null hypothesis of a random walk process (m.d.s.) and variance ratio of one (constant variance ratio). While for the WB-AVR test of Kim (2009), the holding period k is optimally chosen, we choose different holding periods ($k = 2, 5, 10, 30$) for the Wright (2000)'s sign test. It is known that both tests are robust to conditional heteroskedasticity and non-normality. The results of VR tests are presented in Table 2.2.

For Pooled, Phase 1, CB1, and CB2, the random walk hypothesis is rejected in both tests. However, for Phase 2 and CB3, both tests lead to different conclusions. Even though the WB-AVR test, which is based on the magnitude of returns, fails to reject the null of a random walk, the sign tests strongly reject the null. While sign tests are likely more robust to conditional heteroskedasticity and local liquidity, these tests might not be valid when the mean is non-zero (Wright, 2000).[49] In particular, Phase 2 and CB3 are meaningful in the K-ETS because the auction allocation (3% of allowances allocated to firms) is periodically implemented from Phase 2, and the constrained banking is scheduled at the end of each compliance cycle from the middle of Phase 2. Therefore, in the next section, we investigate the long-range dependence in the DFA and local dependencies in a FD study. Specifically, we focus on how the long-range dependence and local dependence change over time when price movements look like a random walk, but dependencies are disrupted by local illiquidity or high volatility, not by a random walk movement.

2.4.2. DFA and FD

We utilize the KAU returns for the DFA analysis (Alvarez-Ramirez et al., 2008; Wang et al., 2011) and the logarithmic KAU prices for the FD analysis (Kristoufek and Vosvrda, 2014; David et al., 2020).[50] The estimated values of Hurst exponent (H) and fractal dimension ($\widehat{D}_{HW}$) are summarized in Table 2.3. For the DFA, we observe that H values are 0.540 and 0.328 for Phase 1 and Phase 2, respectively. In particular, H values in the CB2 and CB3 are below 0.5, indicating that the returns have a short-term memory (anti-persistent process). For the FD, we can clearly see that in all periods $\widehat{D}_{HW}$ values are below 1.5, ranging from 1.000 to 1.449, suggesting that price series show local dependencies (or trends).

To see dynamic movements in returns and price series over time, we conduct a rolling approach using moving windows with 156 observations (the smallest sample size in our sub-sample periods). The time-varying Hurst exponent, shown in the top panel of Figure 2.5, is clearly higher than 0.5 at the beginning of compliance cycles (RA, CB1, and N2) which are not under individually constrained banking. On the other hand, the H value drops below 0.5 when there are structural breaks caused by government intervention day (② and ③ in Figure 2.3). Even though price increases gradually during N2 as seen in Figure 2.3, the H

[49] Although it tests the assumption of i.i.d. series (with heteroskedasticity), Wright's rank test (2000) is also robust to conditional heteroskedasticity in the small sample because it uses the rank of data series instead of the value of the series. In this test, null hypothesis is rejected throughout all sub-sample periods. Results of the rank test are available from the authors upon request.

[50] The DFA for the long-term memory can be applied to both stationary and non-stationary time series. On the other hand, if return series are used in the FD, the measure of the local memory is prone to show an anti-persistent process because return series tend to show alternating signs around the zero mean.

value dramatically decreases at the end of N2. This implies that when there is a small volume of trade at the beginning of cycles, the returns tend to exhibit long-term memory possibly due to sellers' tendencies to hold allowances, while increase in compliance demand introduces short-term memory to price dynamics. In the bottom panel of Figure 2.5 with the FD analysis, we can clearly see that $\widehat{D}_{HW}$ values are below 1.5 in almost all sub-sample periods, implying that the KAU price series has local persistence and trend.[51]

As the end of each compliance cycle (KAU17 and KAU19) in CB2 and CB3 approaches, KAU returns seem to follow a random walk process as the H value in DFA becomes close to 0.5. Note that the H value decreases below 0.4 at the end of CB2 with some price spikes, and it takes some time to recover the H value of 0.5 level during CB3. The FD analysis shows that the price series exhibit a local memory in CB2 and a local increasing trend in CB3 before 2020. In sum, we can see that even under individually constrained banking, unstable price movements and local (increasing) trends do not disappear. The time-varying H and $\widehat{D}_{HW}$ values with different window sizes (120 days and 200 days) also support the above results (see figures B.2.3 and B.2.4 of Appendix B).

2.4.3. Spillovers from other markets

In this section, we examine the relationship between the KAU market and other assets (Dubai oil price and Kospi200 index), focusing on whether other markets are strongly related to abnormal KAU price movements. All return series are stationary, serially correlated, fat-tailed, and have non-normal distribution. The detailed descriptive statistics and the changes in returns can be seen in Table B.2.1 and Figure B.2.5 of Appendix B.

To investigate time-varying spillover effects among three assets, we use 10-day-ahead forecast errors from a linear VAR(5) model and rolling moving windows with 156 observations based on Lanne and Nyberg's GFEVD (2016). As discussed in section 2.3.3, the total spillover index indicates how much forecast error variance of all assets can be explained by the information (or shocks) from other markets and

[51] Figures B.2.1 and B.2.2 of Appendix B present the time-varying Hurst exponent and fractal dimension analysis of Dubai Oil and Kospi200 returns, which we use in section 2.4.3.

the from spillover index indicates how much the return for asset i can be explained by the shocks in other markets.

The time-varying total spillover index among all three assets and from spillovers for each series are plotted in figures B.2.6 and B.2.7 of Appendix B, respectively. Based on the total spillovers, on average, 10.46% of total forecast error variance of all three assets is accounted for by spillovers from other markets throughout all sub-periods. The from spillover index for KAU returns is 8.43% on average, which is lower than the total" spillovers (10.46%) and other assets' from spillovers (12.41% for Dubai oil's return and 10.56% for Kospi200's return).

Furthermore, unlike other assets, the from spillover is never beyond 20% for the KAU returns and there is no sudden change in the from spillover. Considering that there are few sudden spikes in returns of other assets as shown in Figure B.2.5 of Appendix B, there is no strong evidence that abnormal price movements or local increasing trends in KAU prices are due to other markets. Rather, noting that the forecast error variance of KAU's returns can be stably explained by the factors caused by its own market at an average of 91.57% (= 100% - 8.43%), we can infer that those movements are likely due to market internal factors (or market design problems).

2.5. Discussion and Conclusion

We find no statistical evidence that KAU prices fully follow a random walk process. Rather, KAU prices exhibit locally long-term memory with players' tendencies to hold allowances in the beginning of the compliance cycle, leading to unstable price hikes as the compliance demand increases. This implies that firms are suffering from uncertainty about future prices (or compliance costs) exacerbated with expected insufficient market supply. Also, we do not find any strong evidence that other markets influence abnormal price movements in the K-ETS.

This paper first provides valuable lessons about why and how we should control firms' expectations in cap-and-trade, especially under the Paris Agreement which stimulates more ambitious long-term goals. The regulator may seem to prefer the lenient cap with low abatement cost in the initial phases and plan the stricter cap with higher abatement costs in later phases. However, with the intertemporal no-arbitrage condition, the current allowance price may reflect the expectations for the later phases. Although the abatement costs can decrease with the technological advance, firms at the current time may feel that the long-term goal is not achievable and cause even higher abatement costs. Therefore, in addition to the actual implementations, the regulator should deal with such concerns by showing the vision and specific measures to direct stakeholders.

The extreme uncertainty of future prices in the K-ETS may also be due to uncertain price rules for the shortage on market supply. The K-ETS actually has several market stability provisions, including additional auctioning (up to 25% of total reserve amounts) and price ceiling/flooring in addition to the constrained banking. However, which option will be chosen as a market stability measure by the government is also uncertain, and these measures are ex-post tools in that such measures can be implemented only after prices change excessively (Park and Hong, 2014).[52] Even with additional auctioning with price ceiling/flooring, the absence of predetermined price levels is making the variation of firms' expected prices even greater.

Uncertain climate policies could make the situation worse. For example, countries that are recently initializing cap-and-trade systems may suffer more from uncertainties for their NDCs (e.g., uncertain type of targets like BAU or intensity target, conditional target, or absence of the annual emission path). The consequent short-term cap impedes the long-term prediction of allowance prices required for the investment in irreversible abatements with a substantial fixed cost, thus leading firms to hold more allowances for the preparation of an uncertain future.

2.5.1. Possible policy options

Although individually constrained banking can contribute to the increase in trading by forcing firms to sell the surplus allowances in the market, this measure alone cannot be sufficient to control firms'

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[52] In the K-ETS, market stabilization measures can be implemented under the following conditions: a) the allowance price for 6 consecutive months is at least three times higher than the average price of the past 2 years, b) the allowance price for the last month is at least twice the average price of the past 2 years and the average trading volume of the last month is at least twofold the volume of the same month in the past 2 years, and c) it is difficult to trade allowances due to the imbalance between the demand and supply.

expectations of the allowance prices for even the nearby future. That is, even under the constrained banking schedule at the end of the current compliance cycle, the remaining compliance and banking demands in the market can be significantly influenced by the expectation for the high price in the next period. After all, the price can keep going with local increasing trends in CB3. The insufficient information or noise about allowances supplied from firms can also cause temporary unstable movements in CB2 and CB3.

As suggested in Oh et al. (2017), in the K-ETS, the maturity of financial markets to use derivatives to hedge against price risk and to allow non-obligated entities for allowance trading may be one of the options. We here focus on policy options on how to maintain the balance between pursuing ambitious actions and ensuring market efficiencies in the context of the effective implementation of the Paris Agreement. In the K-ETS, individually constrained banking is a good policy option to prevent excessive banking and market powers. However, this measure can be harmonized with the following options.

Flexible supply with the long-term cap: One of the effective options is the soft cap approach suggested by Murrey et al. (2009).[53] Under this approach, allowances will be distributed through the auction at the pre-specified price (p^h) when the allowance price reaches this price level. This approach can lead to the narrower variations of expected prices in advance by providing participants with the signal for the maximum price under the shortage of supply. If the reserve for market stability is also exhausted, allowances additionally obtained through multiple sources (e.g. the reserve for other uses, allowances not sold in the previous auction, and mitigation outcomes from other mechanisms under the Paris Agreement) can be distributed at the higher ceiling price.

Under the short-term cap, since there is no information on the cap (Q_{T+1}) for the market supply ($S_{T+1} = Q_{T+1} - q_{T+1} + b_T$), it would be almost impossible for expectations of future prices to be formulated, causing extremely high variation in the expected price. A long-term cap contributes to promoting price-elastic abatements (especially for irreversible abatements with a high fixed cost) over the

[53] The price-responsive allowance supply framework, suggested by Burtraw et al. (2020), additionally considers the case of low allowance demands for the oversupply problem. Here, when the price is on a price floor (p^l), allowances not sold in the regular auction would be retired.

long term (Borenstein et al., 2019).[54] Consequently, it will function to increase the expectation for lower abatement costs with more abatements.

The increase in the auction allocation: On cap-and-trade systems that rely largely on free allocation, firms additionally suffer from uncertainty in the magnitude of firms' holding tendencies. Here, regarding cap-and-trade systems as a compliance instrument rather than profit opportunities through allowance trading, firms are likely to be subject to endowment effects with regard to their allowance holding (Baudry et al., 2021). The thin market can also cause concern for other firms that require to purchase allowances (Hausker, 1992). When sellers show strong tendencies to hold allowances with the high willingness to accept for KAUs, the auction allocation with some supporting rules (e.g., holding limits or priority at auction to prevent players from acquiring market power) can improve the market efficiency as well as cost-effectiveness. Here, regular auction prices can play a role in price discovery under the thin market or liquidity problem and contribute to the emergence of an active secondary market (Ellerman et al., 2000).

2.5.2. Concluding remarks

Currently, many countries, including developing countries, are at the starting point of the ambitious mitigation actions under the Paris Agreement. Both global and domestic societies expect the cap-and-trade system to play a crucial role in meaningful contributions. For firms in the systems, those atmospheres may be translated into concerns for continuously insufficient market supply. In this context, we looked at why we should focus on firms' expectations of the allowance price formulation and what consequences would be under the expectation of insufficient market supply.

The K-ETS, an important instrument for the Paris Agreement, has experienced liquidity problems with the expectation of the insufficient supply of allowances. In our paper, we find that such expectations can cause critical price hikes and informational inefficiency, which may be caused by uncertainties about prices expected under a shortage of allowances, long-term policy, and the magnitude of banking tendencies. These

[54] The long-term cap can be updated for the higher ambition level based on the realized climate damage. Therefore, this is not in conflict with the provisions (like Article 4, paragraph 11) of the Paris Agreement, which enable the update of NDCs in the direction of enhancing their ambition level.

unintended results can cause additional social costs and even social conflicts, which may impede more ambitious actions regarding climate change. We also explain that individually constrained banking alone cannot be the perfect remedy in that expectations for future price increases can still influence the current allowance price if compliance and banking demands remain.

Market inefficiencies we find in our paper might be due to the small number of players. For the first and second phases in the K-ETS, only obligated firms can participate in the trade. However, starting with the third phase (2021-2025), individual investors can trade allowances in the market and the introduction of derivatives like futures contracts is planned. A future study can investigate how much these measures would contribute to stabilizing the price volatility even under the expectation of insufficient market supply. Such a study would be valuable because most of the mature systems are now experiencing the higher allowance prices with the implementation of the Paris Agreement.

Table 2.1. Descriptive statistics of daily returns of KAU

	Pooled	Phase 1	N1	RA	CB1	CB2	Phase 2	N2	CB3
observations	1117	696	156	188	179	173	421	183	238
mean	0.119	0.106	0.457	0.069	0.088	-0.150	0.140	0.142	0.139
median	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.165
max	9.531	9.531	9.462	4.709	6.351	9.531	6.805	5.705	6.805
min	-10.536	-10.536	0.000	-10.347	-5.497	-10.536	-10.536	-4.082	-10.536
std.dev.	1.735	1.816	1.715	1.570	1.134	2.546	1.593	0.985	1.937
skewness	-0.782	-0.473	4.385	-2.666	0.886	-1.148	-1.513	1.255	-1.618
kurtosis	21.015	21.721	21.693	23.760	14.858	13.164	17.909	14.984	13.773
ADF test	-18.367***	-15.733***	-7.055***	-3.668**	-2.135	-7.041***	-8.299***	-6.914***	-5.969***
PP test	-28.693***	-21.465***	-11.036***	-13.982***	-14.086***	-10.415***	-20.993***	-15.097***	-15.435***
J-B	15218***	10190***	2771***	3599***	1072***	783***	4060***	1143***	1255***

Note: The Augmented Dickey-Fuller (ADF) and the Phillips-Perron (PP) test a null hypothesis of a unit root (non-stationarity) in the equation with constant and time trend. J-B refers to the statistics of the Jarque-Bera test for normality. *, ** and *** are significant at 10%, 5%, and 1% level, respectively.

Table 2.2. Results of VR tests for daily log-returns of KAU

		Pooled	Phase 1	CB1	CB2	Phase 2	CB3
$\boldsymbol{WB-AVR}$		4.085**	4.546***	1.846*	2.387**	0.180	-0.025
$\boldsymbol{JS_1}$		56.798***	50.983***	18.860***	13.281***	20.740***	9.308***
$\boldsymbol{S_1}$	$k=2$	14.990***	13.949***	5.755***	5.702***	6.385***	3.111***
	$k=5$	25.260***	23.986***	9.607***	9.495***	9.859***	4.426***
	$k=10$	35.229***	33.473***	13.269***	11.894***	13.046***	5.483***
	$k=30$	56.798***	50.983***	18.860***	13.281***	20.740***	9.308***

Note: $WB-AVR$ is the Kim (2009)'s wild bootstrap AVR test statistic using the two-point distribution by Mammen (1993). Critical values are obtained with 10,000 replications. S_1 is tested through critical values obtained by simulating s_t with 10,000 replications as in Wright tests (2000) and JS_1 is the Joint Wright test statistic for multiple k values of S_1, which is tested through critical values obtained by simulating the sampling distribution in the same way as those of S_1 as in Kim and Shamsuddin (2008). *, ** and *** indicate significant rejected at 10%, 5%, and 1% level, respectively.

Table 2.3. Results for DFA and FD

		Pooled	**Phase 1**	**CB1**	**CB2**	**Phase 2**	**CB3**
DFA	H	0.499	0.540	0.622	0.416	0.328	0.427
FD	$\widehat{D}_{HW}$	1.208	1.117	1.079	1.177	1.297	1.449

Note: In DFA, Hurst exponent H with $0 < H < 1$ is characterized as follows: a) when $H = 0.5$, the returns with no long-term memory (random walk process), b) when $H > 0.5$, the returns with long-term memory (persistent process), and c) when $H < 0.5$, the returns with short-term memory (anti-persistent process). In FD, fractal dimension from Hall-Wood estimator (Hall and Wood, 2003) $\widehat{D}_{HW}$ with $1 < \widehat{D}_{HW} \leq 2$ is summarized as follows: d) when $\widehat{D}_{HW} = 1.5$, the price series with no local memory (random walk process), ii) when $\widehat{D}_{HW} > 1.5$, the price series with locally short-term memory (anti-persistent process), and iii) when $\widehat{D}_{HW} < 1.5$, the price series with locally long-term memory (persistent process).

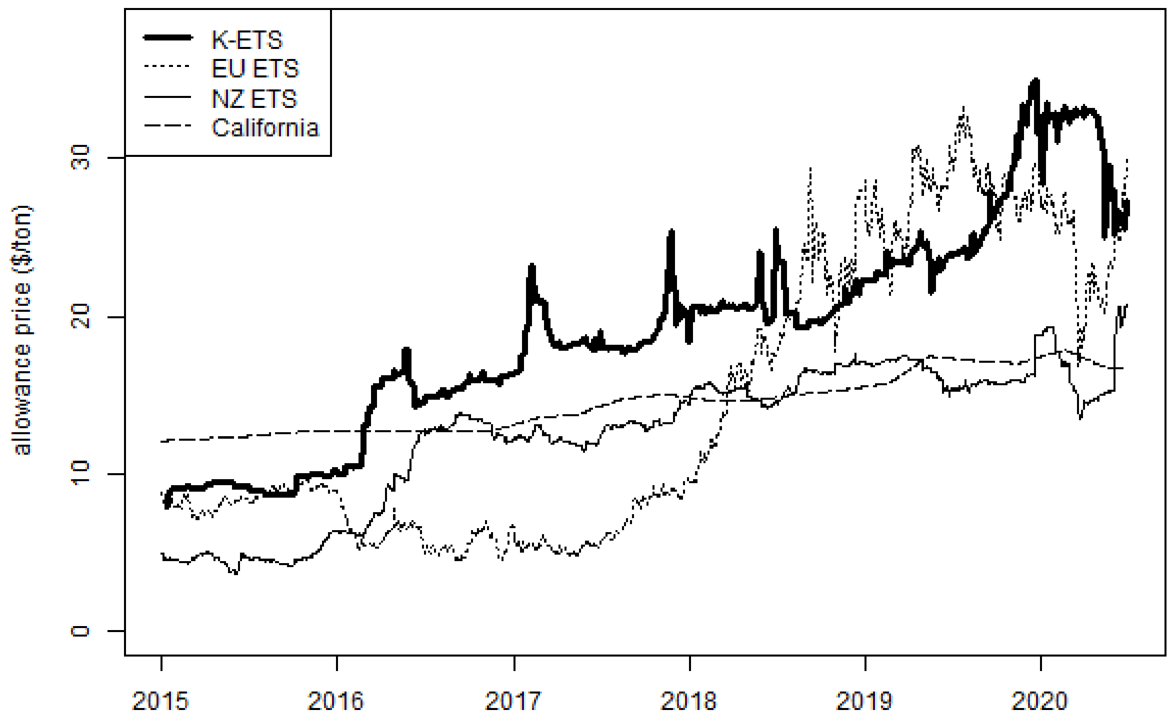
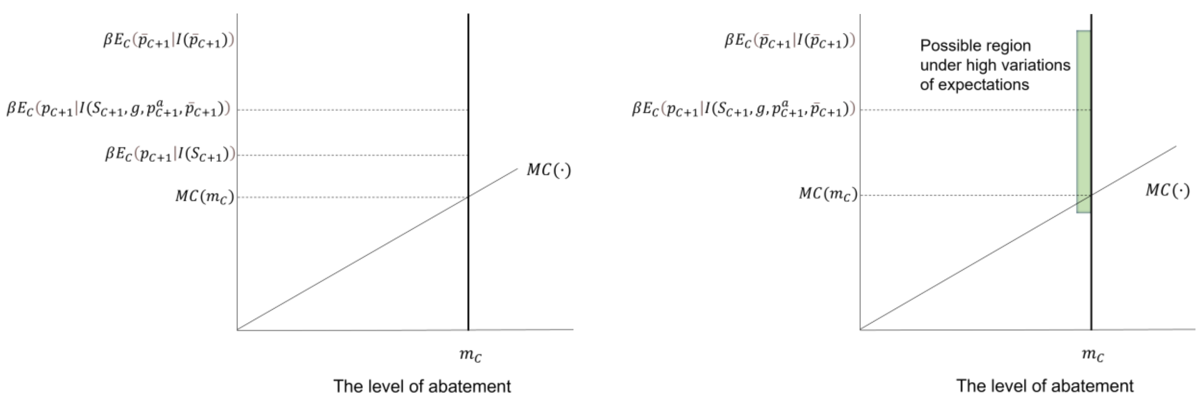


Figure 2.1. Allowance prices from cap-and-trade programs around the world (source: ICAP)

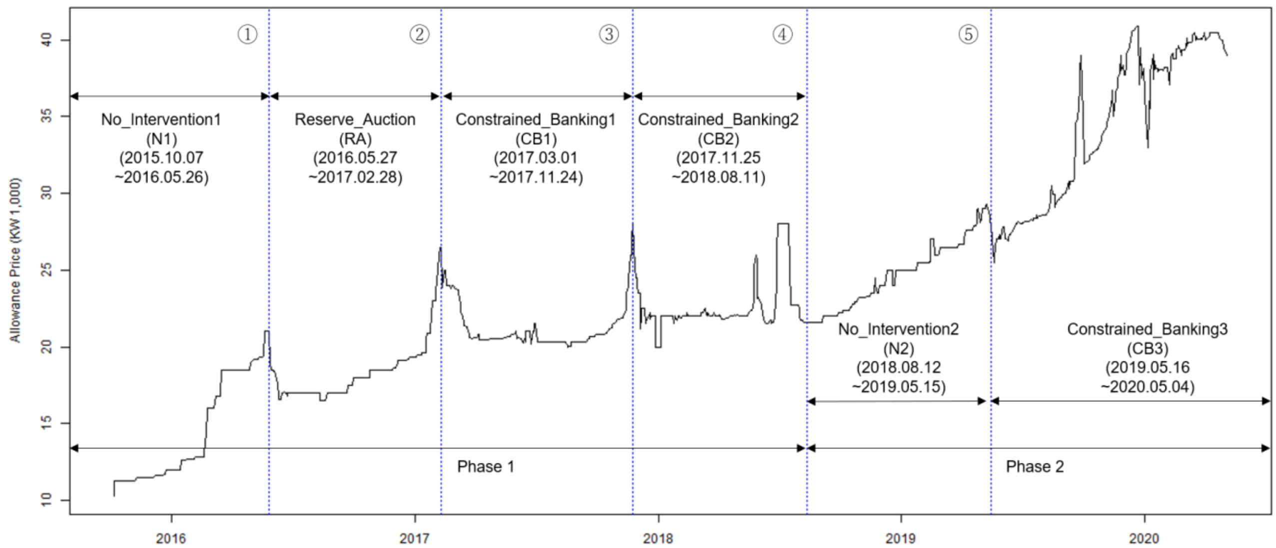
Note: The bold-solid, dotted, thin-solid, long-dashed lines indicate allowance prices for the K-ETS, EU ETS, California's cap and trade program, and New Zealand ETS.



(a) (b)

Figure 2.2. Allowance price formulation and expectation

Note: (a) The case of the representative firm; (b) The case of high variations of expectations from multiple firms



① 2016.05.26 : Announcement of auction for Market Stability Reserve
② 2017.02.28 : Informal announcement of individually constrained banking for KAU17
③ 2017.11.24 : Formal announcement of individually constrained banking for KAU17
④ 2018.08.11 : The last trading day for KAUs of Phase 1 (2015-2017)
⑤ 2019.05.15 : Announcement of individually constrained banking for KAU18, KAU19 and KAU20

Figure 2.3. The changes in the KAU price for the sample period

Note: The sample period is from October 7, 2015 to May 4, 2020. ①, ②, ③, ④, and ⑤ indicate important event days for the sample period.

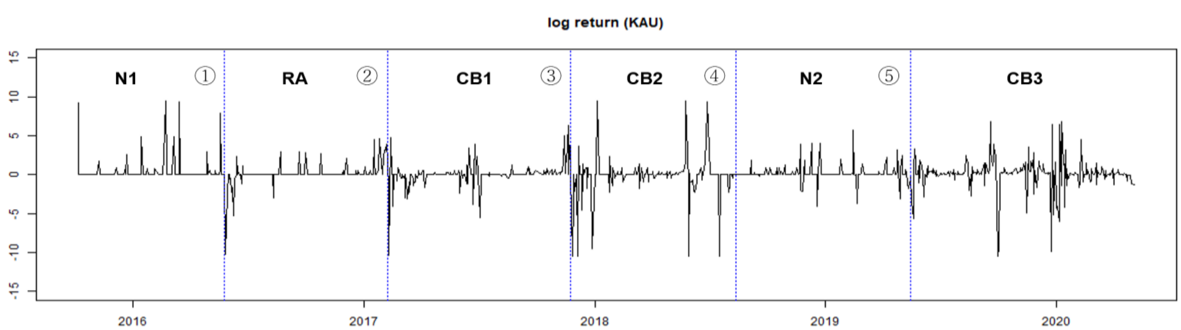


Figure 2.4. The changes in the KAU log-return for the sample period

Note: The sample period is from October 7, 2015 to May 4, 2020. Blue dotted vertical lines indicate important event days (①, ②, ③, ④, and ⑤) in Figure 2.3.

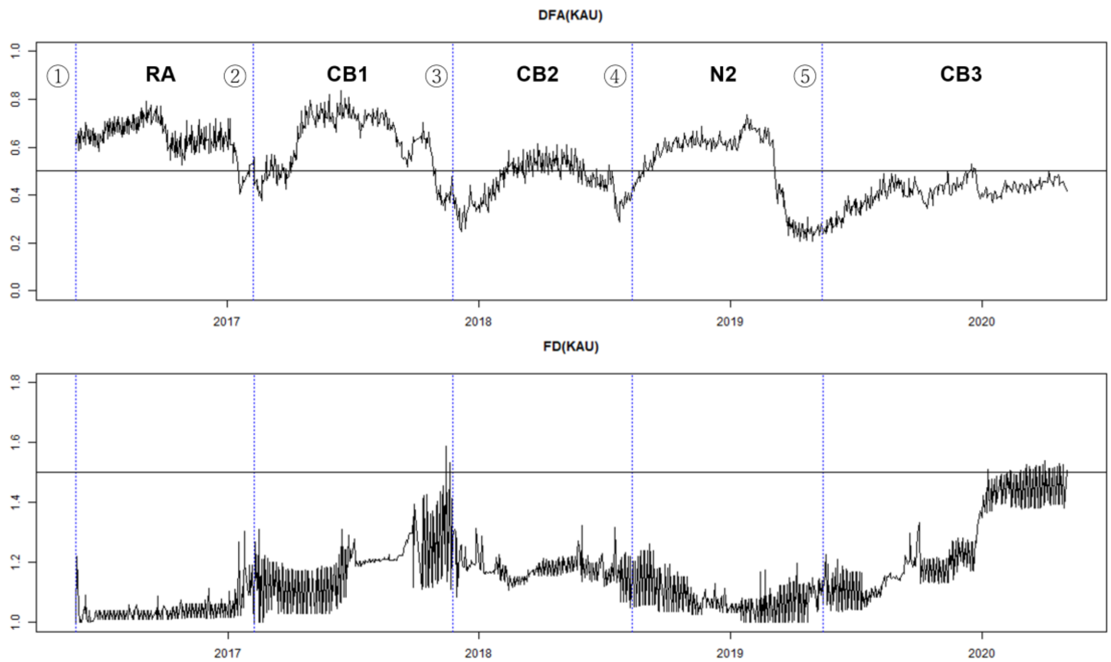


Figure 2.5. Time-varying Hurst exponent and Fractal dimension (Hall-Wood) of the KAU price

Note: The sample period is from October 7, 2015 to May 4, 2020. Black horizontal lines indicate $H = 0.5$ (in the top panel) and $\widehat{D}_{HW} = 1.5$ (in the bottom panel). Blue dotted vertical lines indicate important event days (①, ②, ③, ④, and ⑤) in Figure 2.3.

CHAPTER 3

WEATHER SHOCKS AND VARIABILITIES IN THE AGRICULTURAL PRODUCTION ECONOMY

3.1. INTRODUCTION

Agriculture has strong dependencies and impacts on natural resources. Particularly, agriculture directly uses weather inputs such as temperature, precipitation, or solar radiation in its production process (Lal and Stewart, 2018). Hence, the agricultural economy is more responsive to weather changes than other sectors. The previous literature provides strong empirical evidence that the change in weather conditions has a significant effect on agricultural productivity by directly influencing crop yield (Schlenker and Robert, 2009; Dell et al., 2012; Powell and Reinhard, 2016). That is, droughts, floods, or other weather-related events may cause significant economic costs, especially in the agricultural sector.

When the change of weather patterns is related to climate change, the impacts can be more severe or uncertain. Consolidated research group indicates that the extremity of weather will increase due to climate change (IPCC, 2003). Ortize-Bolbea et al. (2021) empirically show that agricultural productivity growth has been significantly influenced by climate-related weather effects. Extreme weathers are often short-lived, but climate-related extreme weather can persist longer and be problematic by the accumulated weather effects persisted over a long period of time (Walsh et. al., 2014).

These findings have opened the way for the literature that aims at investigating how weather fluctuations affect the agricultural economy, including the effects on production, investment, and consequent prices. McCarl et al. (2008) find that the average climate conditions and their variabilities contribute to average crop yield and their variability. Letta et al. (2021) find that drought conditions significantly increase food prices before harvest periods, and Branco and Féres (2020) examine the effects of rainfalls on household work decisions.

The agricultural system plays an important role in the U.S. economy by ensuring a safe and reliable food supply (about 80% of total U.S. food consumption in 2019), leading a significant amount in U.S. exports (about 7% of total U.S. exports) and contributing to the economies of small towns and rural areas (Joint Economic Committee, 2013).[55] In the U.S., the effects of the climate-related weather are well documented. Liang et al. (2017) show that in distinct regions and seasons temperatures and precipitation explain significant variations in the total factor productivity during 1981-2010, and Ortiz-Bobea et al. (2018) find that agriculture in the U.S. is growing more sensitive to climate Midwestern states during 1960-2004. Moreover, the news about extreme weather continues to be reported recently. For example, the U.S. experienced 22 weather events in 2020, including drought, floods, and hurricanes, where losses are estimated at more than $1 billion. 2020 was unusually wet in the southeast, while the southwest experienced the lowest total precipitation since 2020.[56]

In this study, we investigate the importance of weather shocks, focusing on fluctuations in the U.S. agricultural production. We mainly answer the question about how much main variables in the U.S. agricultural production economy respond to weather shocks. Our contributions to the literature are as follows. First, noting that the U.S. agricultural system is closely connected with other economic agents (households, firms, exporters, etc.) and related sectors (foods, intermediate goods as inputs, agricultural banks, etc.) and that agriculture can be influenced by a wide range of economic shocks and stresses, we use a general equilibrium, considering the U.S. agricultural production economy affected by exogenous weather fluctuations. Second, based on the previous literature, our question might be approached in two ways: by investigating empirical models with a partial equilibrium and reduced-form approach or by focusing on long-term effects through a general equilibrium and calibration approach as integrated assessment models (IAMs). To reconcile the two approaches, we build an estimated dynamic stochastic general equilibrium

[55] Joint Economic Committee: https://www.jec.senate.gov/public/index.cfm/democrats/2013/9/the-economic-contribution-of-america-s-farmers-and-the-importance-of-agricultural-exports.

[56] i) the U.S. nation-wide case: https://www.ncdc.noaa.gov/billions/, ii) the southeast case (NOAA, 2021): https://www.ncdc.noaa.gov/sotc/drought/202013, and, iii) the southwest case (NOAA, 2021): https://www.drought.gov/news/new-noaa-report-exceptional-southwest-drought-exacerbated-human-caused-warming.

(DSGE) model. Consequently, we analyze the effects at the national level rather than the heterogeneity of impacts by regions or crops. Next, with the use of quarterly time-series data, we focus on the short-term effects of weather shocks rather than the change in trends or patterns over a long term. Therefore, our approach is centered on the investigation of short-term responses of variables which are linearized around steady states rather than the change in steady states. Lastly, at the aggregate level, especially in the short-term, considering wide geographic boundaries in the U.S., the agricultural loss can be estimated less sensitive to shocks in the aggregate weather index. Also, weather conditions are locally heterogeneous, and their regional (and seasonal) effects can be uneven in the U.S. agricultural production.[57] Noting that weather-driven losses can be uncertain (aggregate uncertainty of losses), we incorporate the shock in weather-driven losses in addition to the shock in fluctuations of the aggregate weather index.[58] When the weather-loss sensitivity is estimated to be quite low, close to zero, the shock in weather-driven losses can additionally capture the effect of weather events and enable the simulation of extreme weather events.

We develop an estimated DSGE model with multiple sectors. The DSGE model is an approach that investigates the dynamic effects of various external shocks to the agricultural economy and alternative policies, considering reasonable economic frictions and lag structure (Smets and Wouters, 2007). Furthermore, the general equilibrium model allows for a rich set of feedback effects in response to shocks originating from each of the economic environments (Albonico et al., 2019). Although DSGE models are widely used in macroeconomics, few empirical studies for DSGE have been used to examine the agricultural economic variability. A notable exception is Gallic and Vermandel (2020) who build and estimate the DSGE model with a weather-dependent agricultural sector to investigate the weather shock's implication on the economy.

[57] The vast territory of the U.S. covers various climate zones and regional geographical features (e.g., deserts and mountains), which possibly cause the heterogeneity in soils, main crops, groundwater availability for irrigation, or adaptation efforts. Also, as for the regional and seasonal heterogeneity of weather effects in the U.S. agricultural production economy, as, you can see more detail in Wang et al. (2017), Liang et al. (2017), Ortiz-Bobea et al. (2018), and Plastina et al. (2021).

[58] In our study, the term "weather shock" means the combination of the shock in fluctuations of the aggregate weather index and the shock in the weather-driven losses.

Compared to the model of Gallic and Vermandel (2020), there are the following differences. First, instead of rainfalls as a proxy of the severity of a dry or wet status in the soil, we use Palmer drought metrics as in Diffenbaugh et al. (2015) and McCarl et. al. (2008), which calculate the soil moisture index based on weekly data of precipitation, surface air temperature, potential evaporation, water capacity of soil, and historical values of the index. Second, as mentioned above, to reflect the effects of extreme weather events under the aggregate data at the short-term time scale, we additionally introduce a shock of weather-driven losses. Here the persistence and standard deviation of this shock are estimated through Bayesian methods on empirical data in the model. Next, considering that there is an agriculture-specific policy on the interest rates for agricultural investment, we introduce the bank sector. Here, the loan rate for each sector is determined by the policy rate from the central bank and banks' loan portfolios with portfolio adjustment costs suggested by Schmitt-Grohé and Uribe (2003). In addition, we introduced realistic assumptions suitable for the U.S. such as the households as net borrowers in the foreign bond market, and net exports for agricultural goods but the negative trade balance.

In section 3.2, we introduce our model. Section 3.3 discusses the data, calibrated parameters, and the prior distributions. Section 3.4 summarizes the posterior distributions estimated through the Bayesian method and analyzes the empirical results such as the effects of weather shocks with a view to the short-term, and the effects of alternatives to weather shocks (positive technology shocks and negative agricultural loan rate shocks). Section 3.5 summarizes and concludes.

3.2. The Model

We estimate an open economy DSGE model with two sectors producing intermediate goods, households, capital firms, and banks. Following Gallic and Vermandel (2020), the model covers the two intermediate good sectors (agriculture and non-agriculture) and two type of consumptions (the domestic good and the imported good) for each sector. The separated agricultural sector approach allows us to explain the fluctuations of main variables in the agricultural production economy after the weather shocks.

Regarding the effects of weather shocks, in our model, farmers and ranchers from the agricultural sector faces the land conditions affected by unexpected weather conditions.

3.2.1. Households

There is a continuum of identical households indexed by j in the interval $[0,1]$. Each household represents a group that consists of economic entities such as entrepreneurs, bankers, and workers for the non-agricultural sector and farmers, ranchers, and workers for the agricultural sector. Following Moran and Queralto (2018), each household j's expected lifetime utility function is

$$E_0 \sum_{t=0}^{\infty} (\tilde{\beta}_t)^t \left[log(c_t(j) - EH_t) - \chi_h \frac{h_t(j)^{1+\gamma_h}}{1+\gamma_h} \varepsilon_t^H \right] \tag{3.1}$$

whether $c_t(j)$ is the consumption basket, $h_t(j)$ is the hours worked, $\gamma_h > 0$ denotes the inverse Frisch elasticity of labor supply which represents the labor disutility, and ε_t^H is a labor disutility shock, respectively. $\tilde{\beta}_t = \beta \varepsilon_t^H \in (0,1)$, where β is the non-stochastic discount factor and ε_t^H captures a saving shock which implies a shock to the rate of time preference. Each household j chooses the consumption $c_t(j)$ and hours worked $h_t(j)$ to maximizes the expected lifetime utility function subsect to the following budget constraint.

$$\begin{aligned} \sum_s w_t^s h_t^s(j) + r_{t-1}^D d_{t-1}(j) + r_{t-1} b_{t-1}(j) + rer_t r_{t-1}^{RoW} b_{t-1}^{RoW}(j) + TR_t(j) - tax_t(j) \\ = c_t(j) + d_t(j) + b_t(j) + rer_t b_t^{RoW}(j) + p_t^N rer_t \Theta(b_t^{RoW}(j)) \end{aligned} \tag{3.2}$$

where w_t^s is the wage for each sector $s \in \{A, N\}$, rer_t is the real exchange rate (here, if rer_t increases, the value of the foreign currency also increases), and $TR_t(j)$ and $tax_t(j)$ are a lump-sum transfer from the government and a lump-sum tax, respectively.[59] We assume that external habits EH_t is formulated by the aggregate consumption in $t-1$, which implies $EH_t = \alpha_h c_{t-1}$ where $\alpha_h \in (0,1)$.[60] The household saves

[59] Here the relationship between the real (rer_t) and nominal (e_t) exchange rate is $rer_t = e_t(p_t^{RoW}/p_t)$.

[60] Studies using general equilibrium models (e.g., Fuhrer, 2000) have depended on consumption habit to incorporate gradual hump-shaped responses of macro variables to shocks (Havranek et al., 2017). Consumption habit in the model functions to smooth consumption dynamics in the model, putting more costs on abrupt changes in consumption.

their incomes in the form of deposits $d_t(j)$, which are rewarded with returns r_t^D at the end of time t. The household also holds financial assets: domestic bonds $b_t(j)$ and foreign bonds $b_t^{RoW}(j)$. The returns for holding $b_t(j)$ and $b_t^{RoW}(j)$ are r_t and r_t^{RoW} and are paid to household at time $t+1$. Following Schmitt-Grohé and Uribe (2003), we assume that the household needs to pay a portfolio adjustment cost $rer_t\Theta(b_t^{RoW}) = 0.5\kappa_b\left(b_t^{RoW} - \bar{b}^{RoW}\right)^2$ which is paid in terms of the market price of domestic non-agricultural goods (p_t^N) which is the price relative to the consumption price index p_t. It is considered that the U.S. is in the net borrower position ($b_t^{RoW} < 0$).[61] Here, κ_b is the constant parameter for the adjustment and $\bar{b}^{RoW}$ is the level of foreign bonds in the steady state. Also, we denote the household's stochastic discounting factor as $M_{t,t+1} = \tilde{\beta}_t u_{c,t+1}/u_{c,t}$ ($u_{c,t} = 1/(c_t(j) - EH_t)$ is the marginal utility of consumption in time t).

Following Horvath (2000) and Caratittini et al. (2020), the labor supply in the utility function allows for imperfect substitutability between the agricultural and non-agricultural sectors. That is, $h_t(j) = \left[h_t^A(j)^{1+\theta} + h_t^N(j)^{1+\theta}\right]^{\frac{1}{1+\theta}}$. If $\theta = 0$, hours worked between both sectors are perfect substitutes, which implies that each household does not discriminate between the agricultural and non-agricultural sector for the labor supply. The assumption of $\theta > 0$ indicates imperfect substitution of labor supply across both sectors, which captures sector specificity and less respondence to the difference of wages. As in the common DSGE models (Hristov and Hülsewig, 2017; Caratittini et al. 2020), we introduce the scale parameter χ_h so that hours worked are set to the values in the steady state.

Following the literature (Albonico et al. 2020; Ginn and Pourroy, 2020), each household allocates agricultural and non-agricultural goods with the CES consumption basket:

$$c_t(j) = \left[(\pi_C^A)^{\frac{1}{\omega}} c_t^A(j)^{\frac{\omega-1}{\omega}} + (1-\pi_C^A)^{\frac{1}{\omega}} c_t^N(j)^{\frac{\omega-1}{\omega}}\right]^{\frac{\omega}{\omega-1}} \quad (3.3)$$

[61] According to Schmitt-Grohe and Uribe (2003), this adjustment cost also plays a role in ensuring the stationarity in an open economy and useful for closing the model.

where π_C^A and ω are the share of agricultural goods in the total consumption basket $c_t(j)$ and the elasticity of substitution between the agricultural and non-agricultural goods, respectively. Also, in the consumption CES basket for the good from each sector $s \in \{A, N\}$, the consumption of domestic goods ($y_{C,t}^s$) and foreign goods (m_t^s) can be allocated as follows:

$$c_t^s(j) = \left[(1-\pi_{C,M}^s)^{\frac{1}{\varphi_s}} y_{C,t}^s(j)^{\frac{\varphi_s-1}{\varphi_s}} + (\pi_{C,M}^s)^{\frac{1}{\varphi_s}} m_t^s(j)^{\frac{\varphi_s-1}{\varphi_s}}\right]^{\frac{\varphi_s}{\varphi_s-1}} \quad (3.4)$$

where $\pi_{C,M}^s$ and φ_s are the share of imported goods in the good consumption for each sector and the elasticity of substitution between domestic goods and imported goods, respectively. The CES consumption basket leads to the following consumption price index (p_t) on aggregation consumption.

$$p_t = \left[\pi_C^A {p_{C,t}^A}^{1-\omega} + (1-\pi_C^A) {p_{C,t}^N}^{1-\omega}\right]^{\frac{1}{1-\omega}} \quad (3.5)$$

where the consumption price index of each good ($p_{C,t}^A$ and $p_{C,t}^N$) can be defined as follows.

$$p_{C,t}^s = \left[\left(1-\pi_{C,M}^s\right)\left(p_{Y,t}^s\right)^{\varphi_s-1} + \pi_{C,M}^s {p_{M,t}^s}^{\varphi_s-1}\right]^{\frac{1}{1-\varphi_s}} \quad (3.6)$$

Then, the optimal consumption for agricultural and non-agricultural goods is:

$$c_t^A(j) = \pi_C^A c_t(j) \left(\frac{p_{C,t}^A}{p_t}\right)^{-\omega}, \; c_t^N(j) = (1-\pi_C^A) c_t(j) \left(\frac{p_{C,t}^N}{p_t}\right)^{-\omega} \quad (3.7)$$

Likewise, the optimal consumption for domestic and imported goods in each sector is as follows.

$$y_{C,t}^s(j) = (1-\pi_{C,M}^s) c_t^s(j) \left(\frac{p_{Y,t}^s}{p_{C,t}^s}\right)^{-\varphi_s}, \; m_t^s = \pi_{C,M}^s c_t^s(j) \left(\frac{rer_t p_t^{s,RoW}}{p_{C,t}^s}\right)^{-\varphi_s} \quad (3.8)$$

where $p_t^{s,RoW}$ is the foreign price in each sector.

3.2.2. Firms

We first assume that the producers operate firms and produce goods in each sector (y_t^s) with a Cobb-Douglas production technology, using capital (k_{t-1}^s) and labor inputs (h_t^s). Goods produced in each sector are domestically consumed or may be exported to the rest of the world. $\pi_{Y,t}^A$ and $\pi_{Y,t}^N$ are the contribution of the agricultural and non-agricultural good in the total output. We allow deviations from the fixed shares (π_Y^A and π_Y^N) by introducing the shock to the production share (ε_t^Y), i.e. $\pi_{Y,t}^A = \varepsilon_t^Y \pi_Y^A$ and $\pi_{Y,t}^N = 1 - \varepsilon_t^Y \pi_Y^A$.

Non-agricultural sector

At the end of time t, non-agricultural firms purchase the capital k_t^N from the capital supplier at the price q_t^N and puts this capital input into the production at time $t+1$. At the end of time $t+1$, the undepreciated capital $(1-\delta^N)k_t^N$ can be sold at the price q_{t+1}^N. Following Caratittini et al. (2020), firms finance the capital costs with loans from the bank and firms offer a payoff r_t^N on the loan $q_t^N k_t^N$ at the end of time t. Then, at time t, the realized profits of non-agricultural firms (D_t^N) are as follows.

$$\Pi_t^N = p_{Y,t}^N y_t^N - w_t^N h_t^N - r_{t-1}^N q_{t-1}^N k_{t-1}^N + (1-\delta^N) q_t^N k_{t-1}^N$$
$$\text{where } y_t^N = \varepsilon_t^{T_N} {k_{t-1}^N}^{\phi_N} {h_t^N}^{1-\phi_N} \tag{3.9}$$

where $p_{Y,t}^N$, y_t^N, and δ^N are the production price of non-agricultural price relative to p_t and the production for non-agricultural goods, and the depreciation rate of capital, respectively. In the production function, $\varepsilon_t^{T_N}$ is the technology shock in the non-agricultural sector, and ϕ_N is the share of capital in the non-agricultural production.

Agricultural sector

Our study focuses on the investigation of implications from fluctuations driven by the weather in the agricultural sector. For the weather variable ε_t^W in this study, we use the “Palmer” drought metrics as in Diffenbaugh et. al. (2015) and McCarl et. al. (2008). The Palmer Drought Severity Index (PDSI) uses weekly data on precipitation, surface air temperature, potential evaporation, and water capacity of the soil to estimate the soil moisture index and indicates the severity of a dry or wet status in the soil.[62] Here, we use on the Palmer Modified Drought Index (PMDI), which modulates transitions between dry and wet periods.[63]

[62] PDSI typically ranges from -4 to +4. Here, zero (0) is used as normal, negative numbers indicate dry conditions, while positive numbers denote wet conditions. We can reach details on the PSDI calculation at the following link of NOAA Climate Prediction Center: https://www.cpc.ncep.noaa.gov/products/analysis_monitoring/cdus/palmer_drought/wpdanote.shtml.

[63] However, we note that the time series of the PMDI is similar to those of the PSDI on the quarterly scale.

We assume that this weather variable affects the land efficiency in the agricultural production process. Following Hansen and Prescott (2002) and Restuccia et al. (2008) where the land input (l_t) is used in the Cobb-Douglas production function, the following production function is considered:

$$y_t^A = \varepsilon_t^{T_A}(l_{t-1}\Gamma(\varepsilon_t^W))^{\pi_L}\left(\kappa_a {k_{t-1}^A}^{\phi_A} {h_{t-1}^A}^{1-\phi_A}\right)^{1-\pi_L} \tag{3.10}$$

where π_L is the land share in the agricultural production, ϕ_A is the share of capital in the capital-labor composite inputs of the agricultural production, $\varepsilon_t^{T_A}$ is the technology shock in the agricultural sector, and κ_a is the technology parameter to link the agricultural productivity to the productivity in the non-agriculture sector.[64]

Regarding the flow that weather conditions influence the agricultural output, we follow Gallic and Vermandel (2020), where the assumption of the fixed land area is relaxed with the introduction of the land efficiency (l_{t-1}). At the end of time $t-1$, farmers with the land efficiency (l_{t-1}) face unexpected weather conditions (ε_t^W) and their weather effects ($\Gamma(\varepsilon_t^W)$), and agricultural productions are influenced through the change in the land efficiency caused by those weather effects. The land efficiency under the current weather condition ($l_{t-1}\Gamma(\varepsilon_t^W)$) affects the land efficiency at the end of time t (l_{t+1}). Also, at time t, farmers can improve the land by spending the cost z_t on the land such as the costs for use of fertilizer, irrigation, and seeds. Then, the endogenous land efficiency is given by

$$l_t = \left[(1-\delta^L) + \kappa_z z_t^{\gamma_z}/\gamma_z\right] l_{t-1}\Gamma(\varepsilon_t^W) \tag{3.11}$$

where δ^L is the decay rate of the land efficiency. In equation (3.11), $\kappa_z z_t^{\gamma_z}/\gamma_z$ is the function that indicates the land efficiency improvement led by the land cost z_t, and κ_z is the scale parameter so that l_t is set to the value in the steady state. If $\gamma_z > 0$, the land efficiency increases in the land cost z_t.

At the aggregate level, considering the vast territory of the U.S., the land efficiency can be less sensitive to the weather index (i.e., the low weather-loss elasticity), especially in the short term. Moreover, regional and seasonal variations in the magnitude of weather effects can cause the aggregate uncertainty of

[64] This parameter is determined by endogenous variables in the steady state. The high κ_a implies the good applicability of general knowledge for the technology advancement in the agricultural sector (Restuccia et al., 2008).

weather-driven losses.[65] Such variations possibly come from the difference in main crops, soils, adaptation efforts such as sustainable practices (and technologies), etc. Building on Gallic and Vermandel (2020), we adopt the following weather loss function.

$$\Gamma(\varepsilon_t^W) = (\varepsilon_t^W)^{-\alpha_w} \cdot \varepsilon_t^D \tag{3.12}$$

where ε_t^D is the shock in weather-driven losses with the AR(1) process, and α_w is the parameter that links the current weather condition (ε_t^W) to the loss of the land efficiency $\Gamma(\varepsilon_t^W)$, which represents weather-land loss elasticity. That is, we introduce the exogenous shock in weather-driven shocks to capture the aggregate uncertainty of the effects of weather events on land efficiency in addition to the shock in the weather index. Note that when the weather-loss elasticity can be estimated quite low, the effects of weather events on land efficiency are captured by the shock in weather-driven losses (ε_t^D) rather than the shock in weather index.[66]

At time t, the realized profits of farmers (D_t^A) are as follows.

$$\Pi_t^A = p_{Y,t}^A y_t^A - w_t^A h_t^A - r_{t-1}^A q_{t-1}^A k_{t-1}^A + (1-\delta^A) q_t^A k_{t-1}^A - r_{t-1}^A p_{Y,t}^N z_t \tag{3.13}$$

Considering that non-real estate debt of farms is much larger than purchased inputs as farm assets in the U.S., we assume that the land cost z_t finances loans from banks. By the presence of intermediate good uses, the value added in the agricultural sector is $va_t^A = y_t^A - p_t^N z_t$.

3.2.3. Capital suppliers

We assume that capital suppliers are competitive, and capital is sector specific and not mobile between the agricultural and non-agricultural sectors. They rent capital to firms in both sectors and the payment that

[65] Wang et al. (2017) represent that the same degree changes in weather index (temperature or precipitation) will have uneven effects on the U.S. local agricultural productivity. Liang et al. (2017) show that temperature and precipitation in specific agricultural regions and seasons can have significant effects on total factor productivity growth during 1981-2010. Ortiz-Bobea et al. (2018) show that the climatic sensitivity of total factor productivity varies regionally and seasonally. For sixteen states of the U.S., Plastina et al. (2021) show regional differences in weather effects on the growth of total factor productivity.

[66] In the econometrics-based long-term models (Ortiz-Bobea et al., 2021; Acevedo et al., 2020) which do not consider the variability of losses, the effects of weather extremity are captured by using quadratic terms of weather index variables. Although excluding quadratic terms may be problematic in the long term, the use of those terms can be arguable in the short term.

they receive from firms can be used to purchase investment goods that is used as the capital in the next time. Expected profits of capital suppliers can be shown as follows.

$$\Pi_t^I = E_0 \sum_{n=t}^{\infty} M_{0,t} \sum_{s=\{A,N\}} \left[q_t^s i_t^s - \left(1 + \tilde{f}\left(\frac{i_t^s}{i_{t-1}^s}\right)\right) p_{Y,t}^N i_t^s \right] \tag{3.14}$$

where $M_{0,t}$ and i_t^s are the household's stochastic discount factor and investment activities, respectively. $\tilde{f}\left(\frac{i_t^s}{i_{t-1}^s}\right)$ is the investment adjustment costs through the estimated parameter $\tilde{f}''$ as in Moran and Querato (2018) and Adolfson et al. (2014). The flow of capital stock for each sector $s \in \{A, N\}$ is given by $k_t^s = (1-\delta^s)k_{t-1}^s + i_t^s$.

3.2.4. Banks

Banks are assumed to be competitive. They receive deposits from households and lend loans to firms in each sector. At the end of time t, they obtain returns on firms' loans, which are used to pay returns on deposits from households (d_t) at the deposit rate r_t^D. To motivate a simple but non-trivial bank sector, banks are required to maintain the minimum reserve holdings $MR_t = mrd_t$ where mr is the minimum reserve ratio. Expected profits of banks can be represented as follows.

$$\Pi_t^B = \pi_{Y,t}^A r_t^A L_t^A + (1-\pi_{Y,t}^A) r_t^N L_t^N - r_t^D d_t - r_t MR_t - adj_{R,t} \tag{3.15}$$

where $L_t = \pi_{Y,t}^A L_t^A + (1-\pi_{Y,t}^A) L_t^N$ is the aggregate loans and r_t is the policy rate from the central bank. Following Hristov and Hülsewig (2017), we assume that banks choose the optimal loan portfolio by maximizing their expected profits in equation (3.15) by choosing optimal loan supply for each sector subject to their balance sheet constraints ($L_t + MR_t = d_t$).

We consider the sector specific loan rate (r_t^S), considering that each sector faces the different loan rate with the situation that the policy, risk premium for expected loan losses, and entity's properties in each sector are also different. Hristov and Hülsewig (2017). For this cost, we simply assume the portfolio adjustment cost (Schmitt-Grohé and Uribe, 2003) as in the household problem for holding foreign bonds ($adj_{R,t}^s = p_t^N 0.5\kappa_r^s (L_t^s - \bar{L}^s)^2 r_t^s L_t^s$ for $s \in \{A, N\}$). In the household problem, the first order conditions of equation (3.1) and (3.2) implies $r_t^D = r_t$, which corresponds the assumption of Gerali et al. (2010) and Hristov and Hülsewig (2017).

3.2.5. Rest of the world

Focusing on the role of weather shocks for the U.S. agricultural economy, we simply model the foreign sector rather than model it structurally. In our model, the foreign consumption of domestic goods which is equivalent to the domestic is determined by the following exogenous AR(1) process.

$$log\, c_t^{RoW} = (1-\rho_X)\, log\, \bar{c}^{RoW} + \rho_X\, log\, c_{t-1}^{RoW} + \sigma_X \eta_t^C \quad (3.16)$$

where $\eta_t^X \sim N(0,1)$ and $0 \leq \rho_X \leq 1$. We assume that in the steady state the world interest rate (r_t^{RoW}) is the same as the domestic interest rate (r_t), allowing temporary deviations from r_t with the AR(1) process. As in Gallic and Vermandel (2018), with the absence of international sectoral shocks in the model, the foreign prices are synchronized ($p_t^{RoW} = p_t^{s,RoW}$).

3.2.6. Government, aggregation, and market clearing

The government consumes non-agricultural goods (G_t), issues domestic bonds for their debt (b_t) and pays the interest rate on household bonds, provides a lump-sum transfer to households (TR_t) and the international transfer to the rest of the world (ITR_t), and imposes a lump-sum tax on households Tax_t. The government budget constraint is as follows.

$$G_t + ITR_t + r_{t-1}b_{t-1} = b_t + Tax_t - TR_t \quad (3.17)$$

The government expenditure G_t, the lump-sum transfer TR_t, and the international transfer ITR_t are exogenous, i.e. $G_t = \varepsilon_t^G Y_t^N g$, $TR_t = Y_t^N tr$, and $ITR_t = \varepsilon_t^{TR} G_t itr$ where $g, tr, itr \in [0,1]$. The government expenditure shock ε_t^G and international transfer shock ε_t^{TR} follow the AR(1) process.

Aggregation of real GDP y_t, investment i_t, worked hours (H_t), and consumption (c_t) are given by

$$\begin{gathered} y_t = \pi_{Y,t}^A p_{Y,t}^A y_t^A + (1-\pi_{Y,t}^A) p_{Y,t}^N y_t^N,\ i_t = \pi_{Y,t}^A i_t^A + (1-\pi_{Y,t}^A) i_t^N \\ H_t = \pi_{Y,t}^A h_t^A + (1-\pi_{Y,t}^A) h_t^N,\ \int_0^1 c_t(j)dj \end{gathered} \quad (3.18)$$

In the market clearing on the agricultural good, the supply for agricultural goods should be equal to the demand for agricultural goods as follows.

$$\pi_{Y,t}^A y_t^A = y_{C,t}^A + x_t^A - m_t^A \tag{3.19}$$

Here, $x_t^A = \pi_C^A \pi_{C,M}^A \Phi^A c_t^{RoW}$ is the aggregate export for agricultural goods, where π_C^A, $\pi_{C,M}^A$, and Φ^A are the share of agricultural goods in the total consumption, the share of imported goods in the agricultural consumption, and the scale parameter is the export-to-import ratio in the agricultural sector, respectively.[67] Likewise, the market clearing condition on the non-agricultural good can be obtain as follows.

$$\left(1-\pi_{Y,t}^A\right) y_t^N = y_{C,t}^N + x_t^N - m_t^N + i_t + G_t + adj_t \tag{3.20}$$

where adj_t denote the sum of adjustment costs in the model. $x_t^N = \left(1-\pi_C^A\right)\pi_{C,M}^N \Phi^N c_t^{RoW}$ is the aggregate export for non-agricultural goods, where $\pi_{C,M}^N$ is the share of imported goods in the non-agricultural consumption. In the bank sector, $L_t^A = q_t^A k_t^A + p_{y,t}^N z_t$ and $L_t^N = q_t^N k_t^N$. From the market clearing on the good market, the trade balance is as follows.[68]

$$TB_t = y_t - p_t c_t - p_{Y,t}^N (i_t + G_t + adj_t) \tag{3.21}$$

Also, foreign bonds evolve according to

$$rer_t b_t^{RoW} = rer_t r_{t-1}^{RoW} b_{t-1}^{RoW} + TB_t + ITR_t \tag{3.22}$$

3.3. Estimation Methods

We estimate the parameters in the model with Bayesian methods, using quarterly data for the U.S. economy. The estimation process is as follows. First, the solution of the model is written in state-space form and is obtained through a linear approximation to the policy functions in the model. Second, the likelihood function is constructed using the Kalman filter. Third, based on Bayes' theorem, the posterior distribution is established by combining the prior distributions of the parameters with the likelihood

[67] The scale parameter Φ^A adjusts the level of foreign consumption (c_t^{RoW}) in terms of the consumption level. By the assumption of identical households and their CES basket, the aggregate consumption ($y_{C,t}^A$) for domestic goods and the aggregate import (m_t^A) can be derived from the aggregate consumption (c_t). If we set the foreign consumption c_t^{RoW} to the level of the aggregate consumption (c_t) in the steady state, then we can directly compare $y_{C,t}^A$, x_t^A, and m_t^A to each other on the scale of the aggregate consumption (c_t).

[68] In equation (3.21), the scale of each variable is adjusted at the level of y_t.

function. Fourth, posterior distributions of the parameters are obtained by sampling draws from the Metropolis-Hastings methods.[69]

3.3.1. Data

We use nine quarterly time series data over the period 1991Q1-2020Q4 with 120 observations for each variable. Nine observables include real GDP, real consumption, real investment, weakly worked hours, real exports, real value-added for the farm, real food consumption, producer price index for farm products, negative PMDI (nPMDI).[70] For the stationarity, real GDP, real consumption, real investment, real exports, real-value added for the farm, and real food consumption are divided by the working-age population to remove a non-stationarity by the population growth, taken in natural logs, and detrended by a quadratic trend. Following Smets and Wouters (2007), weekly worked hours are multiplied by the employment rate for the working-age population. Corrected worked hours are demeaned after being taken in logs. The producer price index is demeaned after being divided by one lag value, and nPMDI is demeaned.

3.3.2. Calibration

The calibrated parameters are summarized in Table 3.1. The household discounting factor (β) is calculated to 0.99, and the time share of hours worked in the steady state ($\bar{h}^A = \bar{h}^N$) is set to $1/3$ in terms of daily worked hours. Both are common in the DSGE literature. As in Smets and Wouters (2007), the consumption habit is set to 0.7.[71] The household's portfolio adjustment cost parameter $\kappa_b = 0.0007$ is chosen as in Schmitt-Grohé and Uribe (2003) and Gallic and Vermandel (2020). We choose the capital depreciation rate $\delta^K = 0.025$ from various literature including Smets and Wouters (2007) and adopt the

[69] The scale factor is set to ensure an acceptance rate close to 0.25. Before the estimation, the first 100,000 Metropolis-Hastings draws are tuned. In the estimation, the posterior distribution of parameters is estimated generating 800,000 draws and burning in the first 100,000 draws. Furthermore, we simulate four Marcov-Chains for each 80,000 draws. As in Gallic and Vermandel (2020), we assess the convergence based on the multivariate convergence statistics proposed by Brooks and Gerlman (1998).

[70] Real food consumption is associated with wider sector, including farms and its related industries (food, beverage, etc.), than the scope of farms. We solve this scale problem by adjusting the share of the agricultural consumption in the total consumption in the calibration part. Also, taking a negative sign for the PMDI is simply to assign positive signs for dry conditions.

[71] Showing the importance of consumption habit, Fuhrer (2000) estimates this parameter in the range of 0.8-0.9. Christiano et al. (2005) obtain estimates within the range of 0.5-0.7 through a DSGE model.

share of capital in the agricultural production $\phi_A = 0.34$ from the information about farm input costs of USDA ERS and the share of capital in the non-agricultural production $\phi_A = 0.33$ from various sources including Moran and Queralto (2018). The land is set to 2.115 based on the U.S. data.

The share of agricultural goods in total consumption (π_C^A) is set to 0.009 by multiplying the share of real personal food expenditure in total real personal expenditure (0.075) by the share of farm value-added in value-added of its related all industries (0.115). We set the import shares in the agricultural (π_{CM}^A) and non-agricultural sectors (π_{CM}^N) to 0.17 and 0.25, respectively. The export-to-import ratio for each sector (Φ^A and Φ^N) is set to 1.182 and 0.790 considering the shares of exports (π_X) and imports (π_Y) in GDP, and the shares of each good in exports and imports ($\pi_X^A, 1 - \pi_X^A, \pi_M^A,\ 1 - \pi_M^A$).[72]

The minimum reserve ratio for banks (mr) is set to zero based on the ratio as of December 2020 guided by the U.S. Federal Reserve. The share of government expenditure in GDP $g = 0.18$ and the share of government transfer $tr = 0.11$ is obtained from FRED, and the share of international transfer in government expenditure $itr = 0.01$ is also given by Congressional Research Service (2011).[73]

3.3.3. Prior distributions

The remaining parameters are estimated through Bayesian methods, and our prior distributions are either referred from the existing literature or relatively diffuse so that the data becomes more informative rather than our prior distributions. Table 3.2 summarizes the prior distributions for each parameter. Shocks in our model are considered to follow AR(1) process.[74] The parameters of persistence and standard deviation are estimated following Smets and Wouters (2007). In the steady state, these shock processes are all normalized to one. The inverse Frisch elasticity of labor supply (γ_h) and intra-sectoral labor cost (θ) are assumed to be normal with a mean of 1 from various sources (Hristov and Hülsewig, 2017; Caratittini et al. 2020) and with a standard deviation of 0.75 for more diffuse distributions.

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[72] More specifically, $\Phi^A = (\pi_X \pi_X^A)/(\pi_M \pi_M^A)$ and $\Phi^N = [\pi_X(1 - \pi_X^N)]/[\pi_M(1 - \pi_M^A)]$.

[73] Congressional Research Service (2011): https://crsreports.congress.gov/product/pdf/R/R40213.

[74] Here, AR(1) shocks are given in the following form: $log\ \varepsilon_t = \rho\ log\ \varepsilon_{t-1} + \sigma\eta_t$ with $0 \leq \rho \leq 1$ and $\eta_t \sim N(0,1)$.

Based on USDA ERS farm input costs, the land share in the agricultural production (π_L) follows a Beta distribution with a mean and standard deviation of 0.15 and 0.01, respectively. The mean of the land efficiency depreciation rate is assumed to be posterior estimates ($\delta^L = 0.05$) in Gallic and Vermandel (2020) but to be still diffuse with a standard deviation of 0.02 under a Beta distribution. As for the land improvement parameter of expenditure (γ_z), we assume the constant returns with a mean of 1 and a standard deviation of 1 for the diffuse distribution. Following Gallic and Vermandel (2020), the parameter of weather-land efficiency elasticity (α_w) is assumed to be uniformly distributed with a zero mean and a standard deviation of 500. This enables the empirical data to be much more informative for the posterior distribution rather than the information from the prior distribution.

Priors of the investment adjustment cost parameter (κ_i) are based on those in Hristov and Hülsewig (2017). Although the parameter for the portfolio adjustment cost in Schmitt-Grohé and Uribe (2003) is relatively small, we assum that loan adjustment cost parameters (κ_{ra} and κ_{rn}) follow a diffuse Gamma distribution with a mean and standard deviation of 0.1 and 0.05. Following Gallic and Vermandel (2020), the elasticities of substitution for consumptions (ω), agricultural (φ_A) and non-agricultural consumptions (φ_N) are assumed to follow a Gamma distribution such that parameter values are on [0, 5].

3.4. EMPIRICAL RESULTS

3.4.1. Posterior distributions and contemporaneous effects of weather shocks

Table 3.2 also summarizes the means, standard deviations, and the 5th and 95th percentiles of the posterior distributions for each parameter drawn through the Metropolis-Hastings methods. Overall, as indicated by the different means and the lower standard deviations of posterior distributions compared to the prior distributions, it appears that the data are quite informative.

As for the preference parameters, the estimated mean of labor disutility (γ_h) is 5.01.[75] The intra-sectoral labor cost (θ) is 4.98, indicating the imperfect substitutes among both sectors. The elasticity of substitution between both sectors (ω) is estimated to be 6.07. It appears that the substitution between domestic goods and foreign goods is low ($\varphi_A = 0.1$ and $\varphi_A = 0.67$). Regarding the land efficiency, the land share is almost consistent with the data ($\pi_L = 0.15$), the estimated land decay rate is almost equal to one in Gallic and Vermandel (2020) ($\delta^L = 0.081$). The improvement parameter of land costs ($\gamma_z = 1.41$) is low relative to one in Gallic and Vermandel (2020) but is still showing increasing returns to scale.

Note that the mean of the land efficiency – weather index parameter ($\alpha_w = 0.23$) is quite low compared to 20.59 in the case of New Zealand in Gallic and Vermandel (2020). When this elasticity is combined with the land share ($\pi_L = 0.15$), the overall elasticity of the weather index on the agricultural output is almost close to zero ($\alpha_w \times \pi_L = 0.04$).[76] Along with the difference in latitude or climate zone, the low elasticity is possibly due to the use of the aggregate data under the vast territory of the U.S., which covers various climate zones with the change in the latitude or regional geographical features such as deserts and mountains. When the sensitivity to weather index shock is relatively low, the shock in weather-driven losses (ε_t^D) plays a critical role in capturing the aggregate uncertainty of weather effects. For the shock in weather-driven losses (ε_t^D), the estimated persistence and standard deviation are 0.57 and 4.65, respectively. With a view to the contemporaneous effects of a weather-driven shock, the realization of an average weather variation and loss shock (i.e., $\sigma_W \eta_t^W = 1.26$ and $\sigma_D \eta_t^D = 4.65$) may reduce the land efficiency and the agricultural output by 4.9% and 0.8%, respectively. However, with the realization of an extreme loss (i.e., $\sigma_D \eta_t^D = 10.0$), the extreme weather would reduce the agricultural output by 1.7%.

3.4.2. The transmission mechanism of weather shocks

First, to better understand the transmission mechanism of weather shocks, we conduct the impulse response analysis. Figure 3.1 reports the simulated impulse response functions (IRFs) from posterior

[75] This is in line with the result in Smets and Wouters (2007) and Chetty et al. (2011) when employment rates are applied to aggregate hours.

[76] The difference of this elasticity is partially due to different climate zone by the change in latitude

distributions of the main agricultural variables with the combination of a weather index shock ($\eta_t^W = 1$) and a shock in the weather-driven loss ($\eta_t^D = -1$).[77] These shocks function as a negative supply shock, influencing investments, land costs, and their outputs.

A weather condition strongly influences the fluctuations of main agricultural variables with a large decline of land efficiencies (-4.5%) and outputs (-1.2%). To compensate for these losses, farmers and ranchers increase the land costs (-13%), temporarily reducing the agricultural investment excluding the land input costs (-30%). The decreased agricultural output slightly increases the aggregate agricultural price index (0.3%) and the labor demand (-0.15%) slightly decreases with the decline of agricultural outputs.

Note that the land efficiency loss is gradually recovered over 20 periods and that the accumulation of capital stocks is also slowly reverted to the steady state. Here the slow recovery of the capital accumulation level is possibly because the accumulated capital stocks are used for the land costs to recover the land efficiency after the weather shock. That is, the combination of the persistence of land efficiency losses and the almost unchanged investment (excluding the land input costs) with little change in capital price may lead to the persistence of losses in agricultural outputs, which thus increase the cumulative losses of the agricultural output.

3.4.3. The contribution of weather shocks on the aggregate growth (change) variations

Table 3.3 reports the contributions of weather shocks ($\eta_t^W + \eta_t^D$) in the forecasting error variance decomposition for the growth (change) variations of agricultural output, agricultural capital, hours worked, and agricultural price index.[78] Two periods for the growth (one-quarter growth and one-year growth) are considered. Five different time horizons, from two quarters (Q2) to 1 year (Q4), 2 years (Q8), and 5 years (Q20) with unconditional variance decomposition (Q∞), are investigated. Here the contribution of weather shocks includes contributions by both weather index variations and variations of weather-driven losses.

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[77] For IRFs of macro variables to the standard shocks ($\eta_t^W = 1$ and $\eta_t^D = -1$), see Figure C.1 of Appendix C.

[78] In the estimated DSGE model, the results of the forecasting error variance decomposition are subject to shocks used in our model. That is, the contributions of weather shocks are relative to those of shocks used in our model. This is different from the forecasting error variance decomposition in vector autoregression (VAR) models.

For the growth of agricultural output, the contributions of weather shocks are prominent. Based on one-year growth, weather shocks account for 10.2%-19.6% of output growth. In one-year growth, the contributions of weather shocks also become large because of the persistence of losses. In the case of input variables (capital and hours worked), the contributions of weather shocks are not large, with a maximum of less than 1.5%.[79] For the change in the agricultural price index, the result displays that weather contribution is not significant with 1.1% for one-year change at one year time horizon. This may be due to properties of the aggregate price data. Note that it does not mean that under extreme weather events the change in prices is trivial. Our IRF function shows that the agricultural price index can increase by around 0.6% under extreme weather events ($\eta_t^W = 1$ and $\eta_t^D = -2$).

3.4.4. The role of the technology and the temporary adjustment of agricultural loan rates

The slow recovery of losses in agricultural outputs implies that if we put extra effort, cumulative output losses could be offset. Pardey and Alston (2012) indicate that over the period 1910-2007, the high growth in total factor productivity was fueled by publicly funded agricultural research and development (R&D). Baldos et al. (2018) suggest that marginal returns to U.S. public agricultural R&D expenditure might have remained relatively constant over a long time. Here we first investigate the effects of technology progresses, which may be driven by public R&D, by introducing a permanent technical innovation or by assuming the gradual technology progresses.

Figure 3.2 presents the impulse responses of each variable to the abrupt introduction of advanced technologies and the gradual technology progress after an extreme weather shock ($\eta_t^W = 1$ and $\eta_t^D = -2$) at $t = 1$. Given the gradual progress of technology, the decreased agricultural output approaches to the steady state around the 12th period, and after the 12th period, the agricultural output goes to the new steady-state level. That is, the technology progress can not only lead to output growth but also can speed up the

[79] This is because these inputs are more affected by other shocks such as labor supply shocks or saving shocks.

recovery from output losses caused by weather shocks.[80] Also, we can see that under more advanced technologies, weather-driven output losses can be recovered more rapidly.

However, as indicated in Baldos et al. (2018), R&D and technological progress could take a long time to bear fruit, and innovated technologies may not be timely applicable for weather-driven losses that have already occurred. Therefore, we now investigate the effects of adjusting agricultural loan rates by introducing constant negative shocks in agricultural lending rates or by gradually decreasing the degree of shocks after constant negative shocks. It is expected that the decreased output level is more rapidly recovered through more accumulated capital stocks led by the decreased capital price.

Figure 3.3 shows the impulse responses of each variable to constant negative shocks over the periods and gradual adjustment of negative shocks to the previous steady state in the agricultural loan rate after an extreme weather shock at $t = 1$. With a relatively low price for the agricultural capital, the level of accumulated capital stocks is more rapidly reverted to the previous steady-state level. Note that loan rate adjustments could be linked to more climate-resilient agricultural financial system.[81] This linkage will significantly contribute to not only the rapid recovery from weather-driven losses but also the improved adaptability to future weather shocks or climate risks.

3.4.5. Sensitivity analysis

This section investigates the results from sensitivity analysis for three parameters: the persistence of shocks in the weather-driven loss ρ_D, its standard deviation σ_D, and land efficiency depreciation rate δ^L.[82] Those parameters can vary due to the aggregate uncertainty of weather-drivel losses and to the high variation of the land efficiency, which significantly influences the degree of effects caused by weather shocks in our model. To compare the steady state in our model with the responses to shocks, the standard

[80] The improved technologies can also achieve the improved land efficiency or reduce the damage from weather shocks. However, in our model the land efficiency is assumed to be fixed. This implies that our IRFs to technology innovation may be a bit conservative.

[81] For example, loan rates can be designed toward more incentives for sustainable practices, i.e., higher availability of credit to farmers and ranchers transitioning to more climate-resilient practices. Also, the government can consider increasing loan guarantees to agricultural community banks, which are highly vulnerable to climate risks.

[82] For sensitivity analysis for parameters on persistence of shocks in the weather index ρ_W and its standard deviation σ_D, see Figure C.2 and C.3 of Appendix C.

weather shocks ($\eta_t^W = 1$ and $\eta_t^D = -1$) start from $t = 1$. All IRFs are reported as percentage deviations from the steady state of each variable.

We first consider the parameter ρ_D, which indicates the persistence of the instantaneous shock in losses driven from the weather index. The higher ρ_D implies the long-lasting effect of the shock in losses from each weather event. In Figure 3.4, we compare the IRFs in our model using the estimated parameter ($\rho_D = 0.57$) with the lower persistence ($\rho_D = 0.40$) and the higher persistence ($\rho_D = 0.70$). As we increase the value of ρ_D, the maximum responses from losses become a bit larger and the time to those responses also increases slightly.

The parameter σ_D indicates the standard deviation of the shock in the weather-driven loss. In our model, considering that in equation (3.12) the estimated weather-land elasticity α_w is relatively small (i.e., the average losses from shocks in the weather index are small), this parameter value implies the average instantaneous effects of each weather event on the land efficiency. Figure 3.5 shows the IRFs under the estimate in our model ($\sigma_D = 4.65$) and those under the small standard deviation ($\sigma_D = 2.3$) and the large standard deviation ($\sigma_D = 9.3$). We can see that with the extreme weather-driven loss ($\sigma_D = 9.3$), the maximum responses can be critically increased.

Finally, we turn to the land efficiency depreciation rate δ^L from the dynamic flow of the land efficiency in equation (3.11). As mentioned in Gallic and Vermandel (2020), this parameter indicates how quickly the land efficiency and consequent agricultural production economy return to their steady states after the weather shock. In Figure 3.6, under the low value of this parameter ($\delta^L = 0.03$), deviations from the steady state are more persistent, while the steady state of the land cost z_t decreases as the land efficiency slowly recovers from the weather-driven loss. Under the high depreciation rate ($\delta^L = 0.13$), the land cost increases, while the recovery speed of the land efficiency gets faster.

3.5. CONCLUSION

In this study, we discuss how the agricultural economy responds to weather shocks with a view to the short term, using the U.S. data. We developed a multisectoral estimated DSGE model, building on Gallic and Vermandel's model (2021) where the agricultural sector with the land efficiency as the production inputs affected by weather shocks, the previous land efficiency, and farmers' expenditures to recover their damaged efficiency. Recognizing that the aggregate weather index can cause the aggregate uncertainty of losses, especially in the short term or for the regional heterogeneity possibly caused by the vast territory of the U.S., we additionally consider a shock in weather-driven losses with a shock in fluctuations of the aggregate weather index

In our model, the weather-loss elasticity is estimated quite low compared to the case of New Zealand. However, when the variability of weather-driven losses is additionally considered, the overall effects of weather shocks on the fluctuations of main variables in the agricultural economy can be significant even at the aggregate level or in the short term. We also find that with the persistence of land efficiency losses, deviations from the steady-state level of the agricultural output and the capital will persist over a longer period. Here, the slow recovery of the capital is possibly due to the high land cost to regain land efficiency. We emphasize the importance of technology innovations possibly through public R&D and loan rate adjustments, which could be linked to incentives for more sustainable practices or government loan guarantees for agricultural community banks. We specifically show that both policy options would be helpful for the more rapid recovery from weather-driven damages as well as the output growth, contributing to a more resilient agricultural system.

Considering that weather conditions are closely associated with climate change and that related economic costs are being realized, weather-driven fluctuations in the economy will be important research issues in understanding mechanisms and their effects. We focus on the significant effects of weather shocks for one of the most vulnerable sectors at the country level. Our framework can be applied to other vulnerable sectors or can be refined focusing on specific economic or scientific phenomena. Also, we note that the government or banks need to stimulate farmers to choose more resilient practices in their production process to reduce the risk premium caused by climate-related risk in agriculture. Our model can be developed by introducing default situations caused by the extreme weather under no insurance market or by initially considering the provision of policy rates for good practice adopters.

Considering that the loss and its functional form for climate-related weathers is notoriously uncertain (Pindyck, 2013; Simon and Venmans, 2018), we adopted the conservative approach to identify the effect of weather shocks. We focus on the short term but the non-linearity relationship in the long term can be furthered in future studies. Our estimated parameters are overall based on diffuse priors so that the estimated effects of weathers are based on our historical data rather than calibrated parameters from projections. At a high level of CO_2 accumulation and warming, other approaches with more gloomy assumptions may be required. Next, the CO_2 feedback loop in the climate-economy cycle can cause more warming and sudden changes in weather patterns. Weather fluctuations also affect agricultural productivity growth as in (Ortiz-Bobea et al., 2021). Our model has a large room for improvement as in a model that the climate sector (Garth Heutel, 2012; Annicchiarico and Dio, 2015) or the agricultural growth (Lanz et al., 2017) is endogenously determined in the model.

Table 3.1. Calibrated parameters

Parameters		Values	Sources
Preferences			
β	Discount factor	0.99	Various
α_h	Consumption habit	0.7	Various; Smets and Wouters (2007)
π_C^A	Share of agricultural goods in total consumption	0.009	Author adjustments (FRED, food personal expenditure, consumption share in GDP)
π_{CM}^A	Import share in agricultural consumption	0.17	USDA ERS (import value share of consumption)
π_{CM}^N	Import share in consumption, non-agricultural sector	0.25	FRED (real personal expenditure, import goods and services)
Production			
δ^K	Capital depreciation rates	0.025	Various; Smets and Wouters (2007)
$\bar{H}^A, \bar{H}^N$	Time shares of hours worked	1/3	Various
$\bar{l}$	Land per working-age population	2.115	FAO (agricultural land area), FRED (working age population)
π_L	Share of Land in production, agricultural sector	0.15	USDA ERS (farm inputs, land)
ϕ_A	Share of capital in production, agricultural sector	0.34	USDA ERS (farm inputs, capital excluding land)
ϕ_N	Share of capital in production, non-agricultural sector	0.33	Various; Moran and Queralto (2018)
Others			
mr	The minimum reserve ratio for banks	0.00	As of December 2020, the Federal Reserve
g	Share of government expenditure in GDP	0.18	FRED (share of government expenditures in GDP)
tr	Share of government transfer in GDP	0.11	FRED (government social benefits, nominal GDP)
itr	Share of International transfer in government expenditure	0.01	Congressional Research Service (2011)
Import and export			
π_X	Export share in GDP	0.125	FRED (share of exports in GDP)
π_X^A	Agricultural export share in total export	0.063	FRED (share of export in GDP), USDA ERS (agricultural trade)
π_M	Import share in GDP	0.155	FRED (share of imports in GDP)
π_M^A	Agricultural import share in total import	0.043	FRED (share of import in GDP), USDA ERS (agricultural trade)

Table 3.2. Prior and posterior distributions of parameters in the model

	parameters	Prior			Posterior		
		Dist.	Mean	Std.	Mean	5%	95%
Structural parameters							
γ_h	Inverse Frisch elasticity of labor supply (Moran and Queralto, 2018)	N	1	0.75	5.010	4.708	5.318
θ_h	Intersectoral labor cost (Horvath, 2000)	N	1	0.75	3.977	3.719	4.291
π_L	Share of land in agricultural output (Gallic and Vermandel, 2020)	B	0.15	0.01	0.154	0.151	0.159
δ^L	Land efficiency depreciation rate (Gallic and Vermandel, 2020)	B	0.05	0.02	0.081	0.073	0.088
γ_z	Land improvement of expenditure (Gallic and Vermandel, 2020)	N	1	1	1.413	1.256	1.579
α_w	Land efficiency – weather index parameter	U	0	*500*	0.229	-0.114	0.572
κ_i	Investment adjustment cost (Moran and Queralto, 2018)	N	1	0.5	0.620	0.371	0.832
κ_{ra}	Loan adjustment cost, agricultural sector	G	0.1	0.05	0.090	0.063	0.112
κ_{rn}	Loan adjustment cost, non-agricultural sector	G	0.1	0.05	0.006	0.004	0.008
ω	Elasticity of substitution, consumptions	G	2	1	6.071	5.680	6.443
φ_A	Elasticity of substitution, agricultural imports	G	2	1	0.089	0.062	0.116
φ_N	Elasticity of substitution, imports in the rest of sectors	G	2	1	0.666	0.650	0.682
Shock processes AR (1)							
σ_S	Saving (risk) (Std)	IG	0.1	2	0.391	0.250	0.522
σ_H	Labor supply disutility (Std)	IG	0.1	2	4.799	4.182	5.396
σ_{T_A}	Sectoral technology (Std), agricultural sector	IG	0.1	2	3.105	2.313	3.794
σ_Y	Share of agricultural output in GDP (Std)	IG	0.1	2	6.476	5.929	7.074
σ_{T_N}	Sectoral technology (Std), non-agricultural sector	IG	0.1	2	5.044	3.961	6.103
σ_W	Weather (Std)	IG	0.1	2	1.260	1.129	1.388
σ_D	Weather-driven loss (Std)	IG	0.1	2	4.652	3.884	5.555
σ_{R_A}	Agricultural loan rate (Std)	IG	0.1	2	3.958	3.160	5.029
σ_G	Government expenditure (Std)	IG	0.1	2	4.851	4.208	5.544
σ_R	World interest rate (Std)	IG	0.1	2	4.414	3.092	5.623
σ_X	Foreign consumption for domestic goods (Std)	IG	0.1	2	3.308	2.815	3.847
ρ_S	Saving (risk) (persistence)	B	0.5	0.2	0.971	0.952	0.991
ρ_H	Labor supply disutility (persistence)	B	0.5	0.2	0.765	0.637	0.895
ρ_{T_A}	Sectoral technology (persistence), agricultural sector	B	0.5	0.2	0.319	0.230	0.415
ρ_{T_N}	Sectoral technology (persistence), non-agricultural sector	B	0.5	0.2	0.998	0.997	1.000
ρ_Y	Share of agricultural output in GDP (persistence)	B	0.5	0.2	0.532	0.413	0.648
ρ_W	Weather (persistence)	B	0.5	0.2	0.780	0.719	0.836
ρ_D	Weather-driven loss (persistence)	B	0.5	0.2	0.566	0.486	0.639
ρ_{R_A}	Agricultural loan rate (persistence)	B	0.5	0.2	0.126	0.040	0.211
ρ_G	Government expenditure (persistence)	B	0.5	0.2	0.862	0.783	0.941
ρ_R	World interest rate (persistence)	B	0.5	0.2	0.921	0.886	0.960
ρ_X	Foreign consumption for domestic goods (persistence)	B	0.5	0.2	0.989	0.977	1.000

Note: The column "Dist." indicates the prior and posterior distributions, which include Normal (N), Beta (B), Gamma (G), and Inverse Gamma (IG) distributions.

Table 3.3. The contributions of weather shocks to variations in agricultural input/output growth (change)

	Forecasting horizon				
	2	4	8	20	∞
$log(y_t^A/y_{t-1}^A)$	3.38	2.99	3.14	3.26	3.26
$log(y_t^A/y_{t-4}^A)$	10.21	19.57	11.98	12.88	12.83
$log(h_t^A/h_{t-1}^A)$	0.48	0.46	0.47	0.49	0.49
$log(h_t^A/h_{t-4}^A)$	0.78	1.09	0.95	1.03	1.02
$log(k_t^A/k_{t-1}^A)$	0.58	0.57	0.57	0.57	0.56
$log(k_t^A/k_{t-4}^A)$	1.14	1.43	0.92	0.82	0.79
$log\left(p_{Y,t}^A/p_{Y,t-1}^A\right)$	0.47	0.42	0.39	0.37	0.36
$log\left(p_{Y,t}^A/p_{Y,t-4}^A\right)$	0.71	1.07	0.57	0.43	0.41

Note: All shocks in this conditional variance decomposition analysis are treated as AR(1) processes.

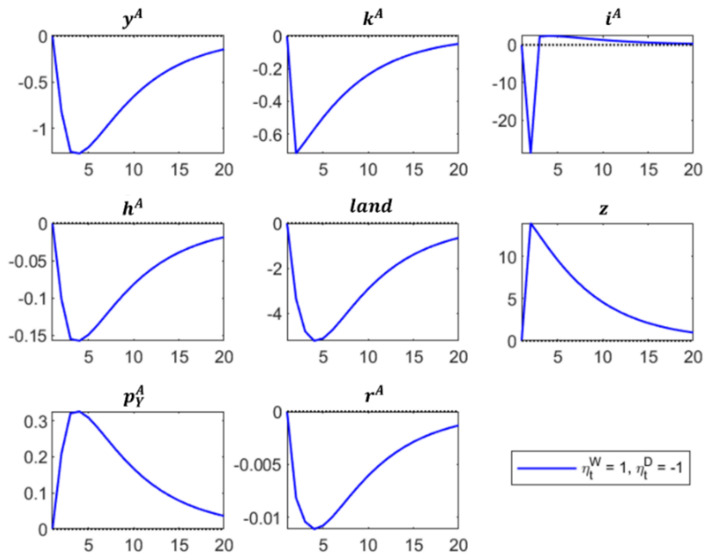

Figure 3.1. IRF of main agricultural variables to a standard weather shock.

Note: IRFs reports percentage deviations from the steady state of each variable after a standard weather shock ($\eta_t^W = 1, \eta_t^D = -1$).

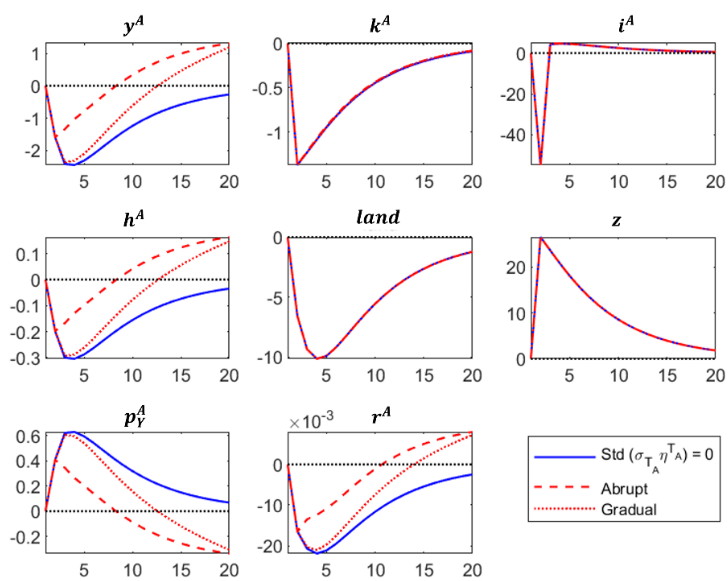

Figure 3.2. IRFs to positive technology shocks (Abrupt vs Gradual)

Note: IRFs reports percentage deviations from the steady state of each variable after an extreme weather shock ($\eta_t^D = -2, \eta_t^W = 1$) at $t = 1$. The red dashed line ('Abrupt') shows the IRF under the permanent positive technology shock with one-standard-deviation ($\sigma_{T_A}\eta^{T_A} = 1$) from $t = 2$, and the red dotted line ('Gradual') displays the IRF under the gradually increased technology shock from zero-standard-deviation at $t = 1$ to one-standard-deviation at $t = 20$.

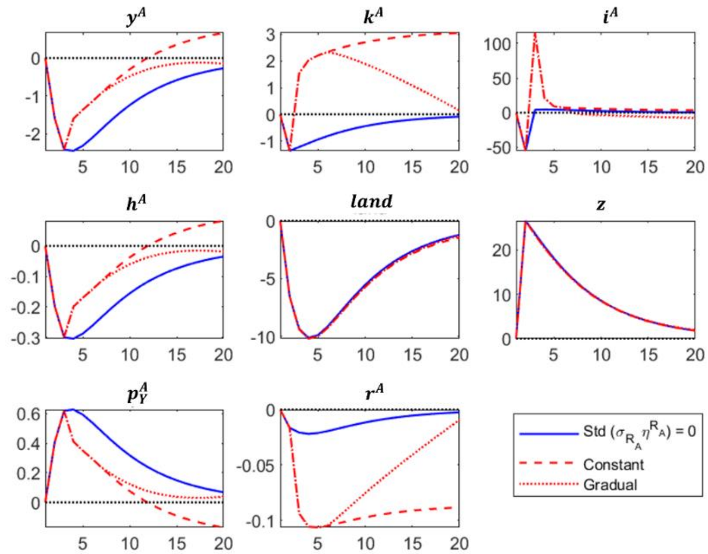

Figure 3.3. IRFs to negative shocks in the agricultural loan rate (Constant vs Gradual)

Note: IRFs reports percentage deviations from the steady state of each variable after an extreme weather shock ($\eta_t^D = -2, \eta_t^W = 1$) at $t = 1$. The red dashed line ('Constant') shows the IRF under constant negative shocks with two-standard-deviation ($\sigma_{R_A}\eta^{R_A} = -2$) from $t = 2$, and the red dotted line ('Gradual') displays the IRF under gradual adjustments from negative two-standard-deviation at $t = 5$ to zero-standard-deviation at $t = 20$.

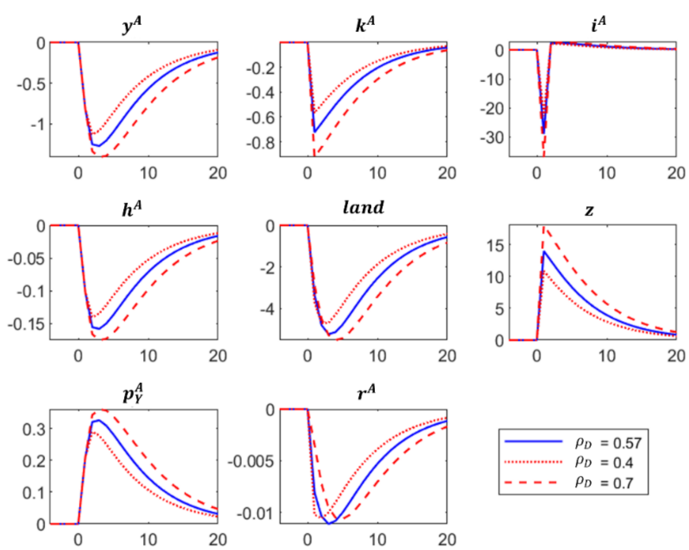

Figure 3.4. Sensitivity analysis to different values of the persistence in weather-driven loss shocks

Note: IRFs reports percentage deviations from the steady state of each variable after a standard weather shock ($\eta_t^D = -1, \eta_t^W = 1$) at $t = 1$. The blue solid line indicates the IRF under the estimated parameter in our model.

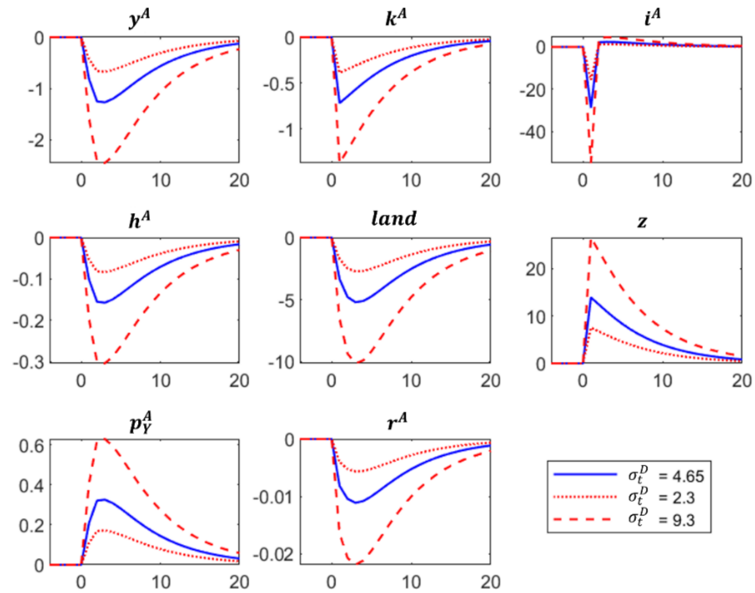

Figure 3.5. Sensitivity analysis to different values of the standard deviation in weather-driven loss shocks.

Note: IRFs reports percentage deviations from the steady state of each variable after a standard weather shock ($\eta_t^D = -1, \eta_t^W = 1$) at $t = 1$. The blue solid line indicates the IRF under the estimated parameter in our model.

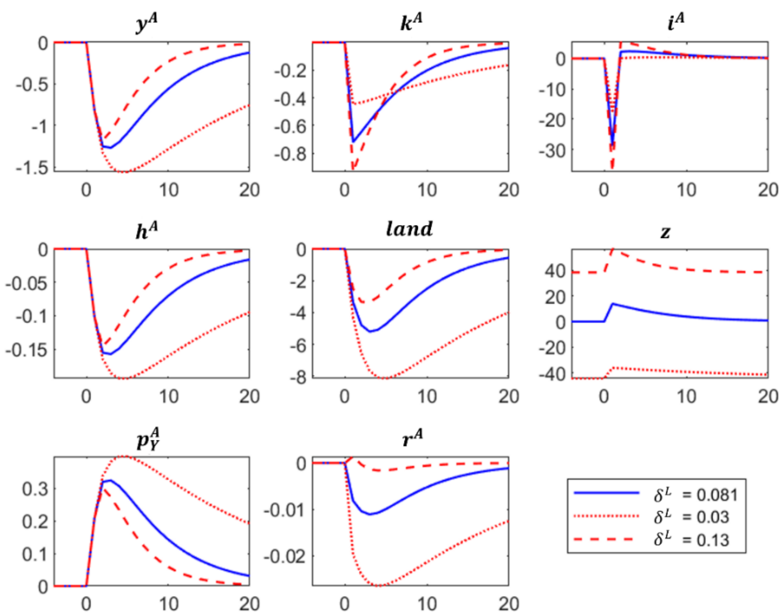

Figure 3.6. Sensitivity analysis to different values of the land efficiency decay rate

Note: IRFs reports percentage deviations from the steady state of each variable after a standard weather shock ($\eta_t^D = -1, \eta_t^W = 1$) at $t = 1$. The blue solid line indicates the IRF under the estimated parameter in our model.

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APPENDIX A

CHAPTER 1 APPENDIX

A.1. Proofs and supporting explanations

A.1.1. "The gain-loss utility decreases with loss-aversion."

Let us denote $F(X(r))$ as the cumulative distribution function of $X(r)$ where $X = W - r$ is a random variable. Then our gain-loss utility can be represented as:

$$\int \mu(X)dF(X) = \int_{X>0} u(X^+)dF(X) + \lambda \cdot \int_{X<0} -u(-X^-)dF(X)$$

We denote $E(\mu(X)|_{\lambda=1})$ as an expected value of $\mu(X)$ when $\lambda = 1$. That is,

$$E(\mu(X)|_{\lambda=1}) = \int_{X>0} u(X^+)dF(X) + \int_{X<0} -u(-X^-)dF(X)$$

Then, our gain-loss utility can be rewritten as follows:

$$\int \mu(X)dF(X) = \underbrace{E(\mu(X)|_{\lambda=1})}_{\substack{gain-loss\ utility \\ in\ case\ of\ loss\ neutral}} + \underbrace{(\lambda - 1)\int_{X<0} -u(-X^-)dF(X)}_{\substack{decrease\ in\ welfare \\ by\ loss\ aversion}}$$

Since $-u(-X^-)$ is negative by the assumption of our gain-loss utility, we can see that the gain-loss utility decreases with loss aversion if $\lambda > 1$. □

A.1.2. "The gain-loss utility satisfies *F.O.S.D.* Theorem."

For any weakly increasing gain-loss utility function $\mu(x)$, assume F *F.O.S.D.* G, which implies $F(x) \leq G(x)$ for any x. Also, let $y(x) = F^{-1}(G(x))$ for any x. If $F(x) \leq G(x)$, it is trivial to show that $y(x) = F^{-1}\big(G(x)\big) \geq x$ for any x. Then,

$$\int \mu(y(x))dF(y(x)) = \int \mu(y(x))dG(x)) \geq \int \mu(x)dG(x)$$

where the equality is by $y(x) = F^{-1}(G(x))$ and the inequality is due to $y(x) \geq x$ and $\mu(\cdot)$ is weakly increasing. □

A.1.3. "The gain-loss utility satisfies *S.O.S.D.* Theorem with simple, reasonable restrictions."

Since $\mu(x)$ is not globally concave (weakly convex if $X < 0$ by the assumption), *S.O.S.D.* Theorem is not applied to the gain-loss utility function. Instead, if we are interested in general cases of the probability distribution like a normal or uniform distribution, with simple restrictions we can induce Proposition A.1 which indicates the relationship between the variance of reference points and gain-loss utility.

Proposition A.1 *Given* $\lambda > 1$, *for any weakly increasing gain-loss utility function* $\mu(x)$, *if (i) the p.d.f.s* f *and* g *are symmetric around the same reference point* 0, *and (ii).* $F(x) \leq G(x)\ if\ x \leq 0$,

$$\int \mu(x)dF(x) \geq \int \mu(x)dG(x)$$

Proof. Let X^+ if $X > 0$ and X^- if $X < 0$ for $X = x, y$. Also, let $y(x) = F^{-1}(G(x))$ for every x. Note that $F(y) \leq G(y)$ for $y < 0$ and $F(y) \geq G(y)$ for $y > 0$ since f and g are symmetric around the same reference point 0 and $F(x) \leq G(x)$ if $x \leq 0$, which implies that $y^-(x^-) \geq x^-$ and $y^+(x^+) \leq x^+$. Then,

$$\int \mu(y(x))dF(y(x)) = \int_{y>0} u(y^+)dF(y) - \lambda \int_{y<0} u(-y^-)dF(y)$$

$$= \int_{x>0} u(y^+)dG(x) - \lambda \int_{x<0} u(-y^-)dG(x)$$

where the second equality is by $y(x) = F^{-1}(G(x))$ or $G(x) = F(y(x))$. And

$$\int \mu(x)dG(x) \quad = \int_{x>0} u(y^+)dG(x) - \lambda \int_{x<0} u(-y^-)dG(x)$$

Then,

$$\int \mu(y)dF(y) - \int \mu(x)dG(x) = \int_{x>0} [u(y^+) - u(x^+)]dG(x) - \lambda \int_{x<0} [u(-y^-) - u(-y^+)]dG(x)$$

Since f and g are symmetric around the reference point, $\int_{x>0} u(y^+)dG(x) = \int_{x<0} u(-y^-)dG(x)$ and $\int_{x>0} u(x^+)dG(x) = \int_{x<0} u(-x^-)dG(x)$. This implies that:

$$\int_{x>0} [u(y^+) - u(x^+)]G(x) = \int_{x<0} [u(-y^-) - u(-x^-)]G(x)$$

That is,

$$\int \mu(y)dF(y) - \int \mu(x)dG(x) = -(\lambda - 1) \int_{x<0} [u(-y^-) - u(-x^-)]dG(x)$$

Since $y^-(x^-) \geq x^-$ implies $-y^-(x^-) \leq -x^-$ and the function $u(-X^-)$ is increasing in $(-X^-)$,

$$u(-y^-) - u(-x^-) \leq 0$$

If $\lambda > 1$, then

$$\int \mu(y)dF(y) - \int \mu(x)dG(x) \geq 0$$

which means $\int \mu(y)dF(y) \geq \int \mu(x)dG(x)$. ☐

A.1.4. Proof of Proposition 1.1 and comparative analysis

Given $\eta > 0$, $\lambda > 1$, the agent's *c.d.f.* (F) of βp_{t+1}, and $u(\cdot) = (\cdot)^\sigma$ $(0 < \sigma \leq 1)$ for gain-loss utility, the following implicit functions (H^i) of $MWTA^i$ and $MWTP^i$ can be derived through equation (5) and *F.O.C.s* with respect to Ts_t^i and Tb_t^i.

$$H_{seller}^i = p_t - \beta E(p_{t+1}) + \eta_s \int_0^{p_t - \beta p_{t+1}} (p_t - \beta p_{t+1})^\sigma \, dF(\beta p_{t+1}) - \eta_s \lambda \int_{p_t - \beta p_{t+1}}^0 \big(-(p_t - \beta p_{t+1})\big)^\sigma \, dF(\beta p_{t+1}) = 0$$

$$H_{buyer}^i = \beta E(p_{t+1}) - p_t + \eta_b \int_0^{\beta p_{t+1} - p_t} (\beta p_{t+1} - p_t)^\sigma \, dF(\beta p_{t+1}) - \eta_b \lambda \int_{\beta p_{t+1} - p_t}^0 \big(-(\beta p_{t+1} - p_t)\big)^\sigma \, dF(\beta p_{t+1}) = 0$$

where $\eta_s = \eta\sigma\left(Ts_t^i\right)^{\sigma-1}$ and $\eta_b = \eta\sigma\left(Tb_t^i\right)^{\sigma-1}$. To show $MWTA^i = \beta E(p_{t+1}) + K_{Ts}$ $(K_{Ts} > 0)$ and $MWTP^i = \beta E(p_{t+1}) - K_{Tb}$ $(K_{Tb} > 0)$, we will use the Leibniz integral rule and intermediate value theorem.

(i) The case of seller

At $p_t = \beta E(p_{t+1})$, $H_{seller}^i\big|_{p_t = \beta E(p_{t+1})} < 0$. That is,

$$\begin{aligned} H_{seller}^i\big|_{p_t=\beta E(p_{t+1})} &= \eta_s \int_0^{\beta E(p_{t+1}) - \beta p_{t+1}} (\beta E(p_{t+1}) - \beta p_{t+1})^\sigma \, dF(\beta p_{t+1}) - \eta_s \lambda \int_{\beta E(p_{t+1}) - \beta p_{t+1}}^0 \big(-(\beta E(p_{t+1}) - \beta p_{t+1})\big)^\sigma \, dF(\beta p_{t+1}) \\ &= -\eta_s(\lambda - 1) \int_{\beta E(p_{t+1}) - \beta p_{t+1}}^0 \big(-(\beta E(p_{t+1}) - \beta p_{t+1})\big)^\sigma \, dF(\beta p_{t+1}) < 0 \end{aligned}$$

Here, since $\int_0^{\beta E(p_{t+1}) - \beta p_{t+1}} (p_t - \beta p_{t+1})^\sigma \, dF(\beta p_{t+1}) = \int_{\beta E(p_{t+1}) - \beta p_{t+1}}^0 \big(-(p_t - \beta p_{t+1})\big)^\sigma \, dF(\beta p_{t+1})$ with the symmetric distribution of βp_{t+1}, the second equality holds. Since $(\cdot)^\sigma$ is also strictly increasing with $0 < \sigma \leq 1$, if $\lambda > 1$, then $H_{seller}^i\big|_{p_t = \beta E(p_{t+1})} < 0$.

Also, at $p_t = D$ where D is high enough to be close to infinity (∞),

$$H_{seller}^i\big|_{p_t = D} > 0.$$

If we show that H_{seller}^i is strictly increasing in p_t, we can prove that a seller has a unique $p_t^* = MWTA^i$ such that $H_{seller}^i\big|_{p_t = MWTA^i} = 0$ and $MWTA^i > \beta E(p_{t+1})$, which implies $MWTA^i = \beta E(p_{t+1}) + K_{Ts}$ $(K_{Ts} > 0)$.

By the Leibniz integral rule,

$$\frac{dH_{seller}^{i}}{dp_t} = 1 + \eta_s \left[\int_0^{p_t - \beta p_{t+1}} \frac{\partial (p_t - \beta p_{t+1})^{\sigma}}{\partial p_t} dF(\beta p_{t+1}) + (p_t - \beta p_{t+1})^{\sigma} \frac{d(p_t - \beta p_{t+1})}{dp_t} \right]$$

$$-\eta_s \lambda \left[\int_{p_t - \beta p_{t+1}}^{0} \frac{\partial \left(-(p_t - \beta p_{t+1})\right)^{\sigma}}{\partial p_t} dF(\beta p_{t+1}) - \left(-(p_t - \beta p_{t+1})\right)^{\sigma} \frac{d(p_t - \beta p_{t+1})}{dp_t} \right]$$

In the second term, since $\frac{\partial (p_t - \beta p_{t+1})^{\sigma}}{\partial p_t} > 0$ and $(p_t - \beta p_{t+1})^{\sigma} > 0$,

$$\eta_s \left[\int_0^{p_t - \beta p_{t+1}} \frac{\partial (p_t - \beta p_{t+1})^{\sigma}}{\partial p_t} dF(\beta p_{t+1}) + (p_t - \beta p_{t+1})^{\sigma} \frac{d(p_t - \beta p_{t+1})}{dp_t} \right] > 0 \text{ for } p_t > \beta p_{t+1}.$$

In the third term, since $\frac{\partial \left(-(p_t - \beta p_{t+1})\right)^{\sigma}}{\partial p_t} < 0$ and $\left(-(p_t - \beta p_{t+1})\right)^{\sigma} > 0$,

$$\eta_s \lambda \left[\int_{p_t - \beta p_{t+1}}^{0} \frac{\partial \left(-(p_t - \beta p_{t+1})\right)^{\sigma}}{\partial p_t} dF(\beta p_{t+1}) - \left(-(p_t - \beta p_{t+1})\right)^{\sigma} \frac{d(p_t - \beta p_{t+1})}{dp_t} \right] < 0 \text{ for } p_t < \beta p_{t+1}.$$

Therefore,

$$\frac{dH_{seller}^{i}}{dp_t} > 0$$

(ii) Comparative analysis for the case of seller

By the symmetric distribution of βp_{t+1}, the *F.O.C.s* with respect to Ts_t^i will be

$$H_{seller}^{i} = -\beta E(p_{t+1}) - \eta_s(\lambda - 1) \int_{p_t - \beta p_{t+1}}^{0} \left(-(p_t - \beta p_{t+1})\right)^{\sigma} dF(\beta p_{t+1}) = 0$$

If $\lambda = 1$, then the *F.O.C.* of the seller's problem ($H_{seller}^{i} = 0$) is simplified into $p_t = \beta E(p_{t+1})$, which means that $\beta E(p_{t+1})$ is a seller's $MWTA^i$.

By the implicit function theorem,

$$\frac{dMWTA^i}{d\lambda} = -\frac{\partial H_{seller}^{i}}{\partial \lambda} \Big/ \frac{\partial H_{seller}^{i}}{\partial MWTA^i} \text{ and } \frac{dMWTA^i}{d\eta_s} = -\frac{\partial H_{seller}^{i}}{\partial \eta_s} \Big/ \frac{\partial H_{seller}^{i}}{\partial MWTA^i}.$$

Since $\frac{\partial H_{seller}^{i}}{\partial \lambda} = -\eta_s \int_{p_t - \beta p_{t+1}}^{0} \left(-(p_t - \beta p_{t+1})\right)^{\sigma} dF(\beta p_{t+1}) < 0$ and $\frac{\partial H_{seller}^{i}}{\partial MWTA^i} > 0$ because $\frac{dH_{seller}^{i}}{dp_t} > 0$,

$$\frac{dMWTA^i}{d\lambda} > 0$$

Also, with the symmetric assupmtion of βp_{t+1}, the equilibrium ($MWTA^i = \beta E(p_{t+1}) + K_{Ts}$) implies

$$\eta_s \int_0^{p_t - \beta p_{t+1}} (p_t - \beta p_{t+1})^{\sigma} dF(\beta p_{t+1}) > \eta_s \lambda \int_{p_t - \beta p_{t+1}}^{0} \left(-(p_t - \beta p_{t+1})\right)^{\sigma} dF(\beta p_{t+1})$$

That is, given $\eta_s > 0$ and $\lambda > 1$,

$$\frac{\partial H_{seller}^i}{\partial \eta_s} = \int_0^{p_t - \beta p_{t+1}} (p_t - \beta p_{t+1})^\sigma \, dF(\beta p_{t+1}) - \lambda \int_{p_t - \beta p_{t+1}}^0 \left(-(p_t - \beta p_{t+1})\right)^\sigma dF(\beta p_{t+1}) > 0$$

Therefore,

$$\frac{dMWTA^i}{d\eta_s} > 0$$

(iii) The case of buyer

Likewise, with the same methods, we can prove that

$$MWTP^i = \beta E(p_{t+1}) - K_{Tb} \ (K_{Tb} > 0), \frac{dMWTP^i}{d\lambda} < 0, \text{ and } \frac{dMWTP^i}{d\eta_s} < 0.$$

. □

A.1.5. The reservation price of the agent with current compliance demands

Suppose that agents with the compliance demand are still searching for allowances at the price as low as possible in the market and that one of other players offers the allowances at the price p_t^x such that $p_t^x > \beta E(p_{t+1})$. This price can be offered publicly at the market or privately through over-the-counter trading. For simplicity, we also assume that if the agent decides to accept the current price offer p_t^x, he can obtain the allowances at the p_t^x with certainty. Then, the choice of the agent can be done to choosing between accepting the price p_t^x or waiting for the next one (p_t^y) in the current period. Then, we can model the choice of accepting the offer or drawing the next one, based on the framework of Lucas, Stokey, and Prescott (1989).

$$V(p_t^x) = max \left[U(X \mid p_t^x), U(X \mid E(p_t^y))\right]$$

where $U(X \mid p_t^x)$ is his total utility level when he accepts the current price offer (p_t^x) and $U(X \mid E(p_t^y))$ is his total utility when he waits for next offers. That is, he will decide on whether he accepts the p^x by comparing his total utility level between both options. Let us denote $z = p_t^x - p_t^y$, z^+ if $z > 0$, and z^- if $z < 0$. Here, the total utilities for accepting the current offer is $U(X \mid p_t^x) = W_{NT}^i - Tc_t^i p_t^x$, and the total utilities for drawing a new one is $U\left(X \mid E\left(p_t^y\right)\right) = W_{NT}^i - Tc_t^i E^i\left(p_t^y\right) + \eta_c \int_0^{p_t^x - p_t^y} \left(Tc_t^i \cdot z^+\right)^\sigma dF\left(p_t^y\right) - \eta_c \lambda \int_{p_t^x - p_t^y}^0 \left(Tc_t^i \cdot (-z^-)\right)^\sigma dF\left(p_t^y\right)$.

Suppose the agent face the compliance demand Tc_t^i at the current period t. Then, after putting both total utility levels equal and isolating p_t^{x*}, we can obtain the agent's reservation price p_t^{x*} as follows:

$$p_t^x = E\left(p_t^y\right) + \eta_c \lambda \int_{p_t^x - p_t^y}^0 (-z^-)^\sigma \, dF\left(p_t^y\right) - \eta_c \int_0^{p_t^x - p_t^y} (z^+)^\sigma \, dF\left(p_t^y\right)$$

where $\eta_c = (Tc_t^i)^{\sigma - 1}$. If we use the same methods as those in proofs of Proposition 1.1 in Appendix A.1.4,

$$p_t^{x*} = E\left(p_t^y\right) + K_c \quad (K_c > 0)$$

$$\left(\frac{dp_t^{x*}}{d\lambda} > 0 \text{ and } \frac{dp_t^{x*}}{d\eta_c} > 0\right)$$

The above equation indicates that the reservation price of the compliance demander depends on his expected price for the next offer (p_t^y), the degree of the weight for gain-loss utility (η), the degree of loss aversion (λ), and the probability distribution of p_t^y. As the deadline approaches, the probability of $p_t^x < p_t^y$ increases, which implies that his reservation price p_t^{x*} increases regardless of his expected future price $\beta E(p_{t+1})$. In this situation, reference dependence and loss aversion play a role in increasing his reservation price p_t^x.

Note that if the firm has the compliance demand under high penalty for compliance failure, his reference price will be switched from βp_{t+1} into the expectation of the next offer price p_t^y. That is, the reservation price for the compliance demander is directly related to his expectation of next offer price (p_t^y). This implies that compliance demanders will buy allowances, depending on other players' *MWTAs* and that their compliance demands get much less price-elastic. Although the current price offer (p_t^x) highly exceeds $\beta E(p_{t+1})$, he may accept the current price offer p_t^x.

A.1.6. Proof of Proposition 1.3

Since $F(\beta p_{t+1}) \leq G(\beta p_{t+1})$ if $\beta E(p_{t+1}) \leq \beta p_{t+1}$ and their *p.d.f.* f and g are symmetric distributions around the same mean $\beta E(p_{t+1})$, G is a mean-preserving spread of F. That is, the variance under G is higher than that under F. If we can prove the case for a seller, we can also apply this proof to the case for a buyer. For simplicity, we let $m = MWTA_F^i - \beta p_{t+1}$, m^+ if $m > 0$, and m^- if $m < 0$. In Appendix A.1.4, on equilibrium, the first-order condition under F is

$$MWTA_F^i = \beta E(p_{t+1}) + \eta_s \lambda \int_{MWTA_F^i - \beta p_{t+1}}^{0} (-m^-)^\sigma dF(\beta p_{t+1}) - \eta_s \int_0^{MWTA_F^i - \beta p_{t+1}} dF(\beta p_{t+1})$$

Note that $MWTA^i > \beta E(p_{t+1})$ on equilibrium by Proposition 1.1 and f is symmetric around the point m such that $m = MWTA_F^i - \beta E(p_{t+1})$. Then,

$$\begin{aligned} MWTA_F^i &= \beta E(p_{t+1}) \underbrace{-\eta_s \lambda \int_{MWTA_F^i - \beta p_{t+1}}^{0} -(-m^-)^\sigma dF(\beta p_{t+1})}_{ⓐ} \\ &\quad \underbrace{-\eta_s \int_0^{MWTA_F^i - \beta E(p_{t+1})} (m^+)^\sigma dF(\beta p_{t+1})}_{ⓑ} \underbrace{-\eta_s \int_{MWTA_F^i - \beta E(p_{t+1})}^{MWTA_F^i - \beta p_{t+1}} (m^+)^\sigma dF(\beta p_{t+1})}_{ⓒ} \end{aligned}$$

Now, we will see what happens to the above first-order condition if we just replace $f(m)$ with $g(m)$ which is symmetric with same mean as $f(m)$. Let us denote $p_{t,G,MWTA_F^i}$ as

$$\begin{aligned} p_{t,G,MWTA_F^i} &= \beta E(p_{t+1}) \underbrace{-\eta_s \lambda \int_{MWTA_F^i - \beta p_{t+1}}^{0} -(-m^{i-})^\sigma dG(\beta p_{t+1})}_{ⓐ} \\ &\quad \underbrace{-\eta_s \int_0^{MWTA_F^i - \beta E(p_{t+1})} (m^+)^\sigma dG(\beta p_{t+1})}_{ⓑ} \underbrace{-\eta_s \int_{MWTA_F^i - \beta E(p_{t+1})}^{MWTA_F^i - \beta p_{t+1}} (m^+)^\sigma dG(\beta p_{t+1})}_{ⓒ} \end{aligned}$$

$F \leq G$ if $m \leq MWTA_F^i - \beta E(p_{t+1})$ ($\beta E(p_{t+1}) \leq \beta p_{t+1}$) and $F \geq G$ if $m \geq MWTA_F^i - \beta E(p_{t+1})$ ($\beta E(p_{t+1}) \geq \beta p_{t+1}$) by the assumption. Also, given $\eta > 0$, $\lambda > 1$ and $0 < \sigma \leq 1$ in $u(\cdot)$, since

$-(-m^-)^\sigma$ and $(m^+)^\sigma$ in ⓐ, ⓑ, and ⓒ are weakly increasing for m, we can apply the first-order stochastic dominance to both sides around symmetric point $(MWTA_F^i - \beta E(p_{t+1}))$. Then, in ⓐ and ⓑ,

$$① \quad = -\eta_s \left\{ \left(\lambda \int_{MWTA_F^i - \beta p_{t+1}}^{0} -(-m^-)^\sigma dG(\beta p_{t+1}) + \int_0^{MWTA_F^i - \beta E(p_{t+1})} (m^+)^\sigma dG(\beta p_{t+1}) \right) - \left(\lambda \int_{MWTA_F^i - \beta p_{t+1}}^{0} -(-m^{i-})^\sigma dF(\beta p_{t+1}) + \int_0^{MWTA_F^i - \beta E(p_{t+1})} (m^+)^\sigma dF(\beta p_{t+1}) \right) \right\} \geq 0$$

In ⓒ,

$$② \quad = -\eta_s \left\{ \int_{MWTA_F^i - \beta E(p_{t+1})}^{MWTA_F^i - \beta p_{t+1}} (m^+)^\sigma dG(\beta p_{t+1}) - \int_{MWTA_F^i - \beta E(p_{t+1})}^{MWTA_F^i - \beta p_{t+1}} (m^+)^\sigma dF(\beta p_{t+1}) \right\} \leq 0$$

Here ① is about the left-side of f and g, and ② is about the right-side of f and g since both f and g are symmetric around $MWTA_F^i - \beta E(p_{t+1})$. Note that $p_{t,G,MWTA_F^i} - MWTA_F^i = ① + ②$. We will obtain $p_{t,G,MWTA_F^i} - MWTA_F^i \geq 0$ by showing ① + ② ≥ 0. For ① + ② ≥ 0, we need the following lemma.

Lemma A.1. *For any weakly increasing function $v(\cdot)$, suppose that F* first-order stochastically dominates *G on $[a, b]$. That is, $\int_a^b v(m)f(m)dm \geq \int_a^b v(m)g(m)dm$.*

Then, as $v'(x)$ increases, $\int_a^b v(m)f(m)dm - \int_a^b v(m)g(m)dm$ (≥ 0) also increases.

Proof. By integration by parts,

$$\int_a^b v(m)f(m)dm = [v(m) \cdot F(m)]_a^b - \int_a^b v'(m)F(m)dm$$

$$= v(b) - \int_a^b v'(m)F(m)dm$$

Then,

$$\int_a^b v(m)f(m)dm - \int_a^b v(m)g(m)dm = \int_a^b v'(m)[G(m) - F(m)]dm$$

□

Given $\eta > 0$, $\lambda > 1$, $0 < \sigma \leq 1$ in $u(\cdot)$ and symmetric distribution of βp_{t+1} around $\beta E(p_{t+1})$, we can see that the absolute values of slopes of $-(-m^-)^\sigma$ and $(m^+)^\sigma$ on the left-side of f and g (the part of $m \leq MWTA_F^i - \beta E(p_{t+1})$ in ①) are entirely larger than those of $(m^+)^\sigma$ on the right-side of f and g (the part of $m \geq MWTA_F^i - \beta E(p_{t+1})$ in ②). Then, by Lemma A.5.1, we can know ① + ② ≥ 0, which implies:

$$MWTA_F^i \leq p_{t,G,MWTA_F^i} = \beta E(p_{t+1}) + \eta_s \lambda \int_{MWTA_F^i - \beta p_{t+1}}^{0} (-m^-)^\sigma dG(\beta p_{t+1}) - \eta_s \int_0^{MWTA_F^i - \beta p_{t+1}} dG(\beta p_{t+1})$$

Using the Leibniz integral rule as in Appendix A.1.4, we can find

$$\frac{dp_{t,G,MWTA_F^i}}{dMWTA_F^i} < 0$$

That is, if $MWTA^i$ increases from $MWTA_F^i$ to $MWTA_F^i + \delta$ ($\delta \geq 0$), $p_{t,G,MWTA_F^i}$ decreases to $p_{t,G,MWTA_F^i+\delta}$, which implies that we can find $MWTA_G^i = MWTA_F^i + \alpha$ under G on which the equilibrium is achieved. Therefore,

$$MWTA_F^i \leq MWTA_G^i$$

Likewise, we can find that $MWTP^i$ under G is lower than $MWTP^i$ under F for a buyer. □

A.2. Definitions and Theorems

Definition A.1. *(F.O.S.D.) For any c.d.f.* F *and* G, F first-order stochastically dominates G *if and only if*

$$F(x) \leq G(x) \quad for\ any\ x$$

Definition A.2. *(S.O.S.D.) For any c.d.f.* F *and* G, F second-order stochastically dominates G *if and only if*

$$\int_{-\infty}^{z} F(x)dx \leq \int_{-\infty}^{z} G(x)dx \quad for\ any\ z$$

Definition A.3 *(M.P.S.) For any c.d.f.* F *and* G, G *is a* mean-preserving spread *of* F *if and only if*

$$y = x + \varepsilon$$

$$(for\ some\ x \sim F, y \sim G, and\ \varepsilon\ such\ that\ E(\ \varepsilon \mid x\ ) = 0\ for\ all\ x)$$

Theorem A.1. *(F.O.S.D. theorem) The followings are equivalent*

1. *For every increasing function* v, $\int v(x)dF(x) \geq \int v(x)dG(x)$.
2. *For any* x, $F(x) \leq G(x)$.

Theorem A.2. *(S.O.S.D. theorem) For any c.d.f.* F *and* G *with the same mean, the followings are equivalent*

1. *For every weakly increasing concave function* v, $\int v(x)dF(x) \geq \int v(x)dG(x)$
2. G *is a mean-preserving spread of F*
3. *For any z,* $\int_{-\infty}^{z} F(x)dx \leq \int_{-\infty}^{z} G(x)dx$

A.3. Supporting tables and figures

Table A.3.1. The heterogeneity effect of λ on R_{MWTA} based on previous literatures.

	λ	$dist$	R_{MWTA}				
			$\eta_s = 0.5$	$\eta_s = 1$	$\eta_s = 2$	$\eta_s = 5$	$\eta = +\infty$
Barberis (2013)	2.25	log-normal	1.061	1.086	1.108	1.128	1.146
		t-normal	1.076	1.105	1.131	1.154	1.174
Tanaka et al. (2010)	2.63	log-normal	1.078	1.108	1.135	1.158	1.179
		t-normal	1.095	1.129	1.159	1.186	1.209
Liu (2013)	3.47	log-normal	1.111	1.151	1.184	1.213	1.240
		t-normal	1.131	1.175	1.212	1.243	1.270
Heutel (2019)	3.50	log-normal	1.112	1.152	1.186	1.215	1.241
		t-normal	1.133	1.177	1.214	1.245	1.272

(a) log-normal distribution (b) truncated normal distribution

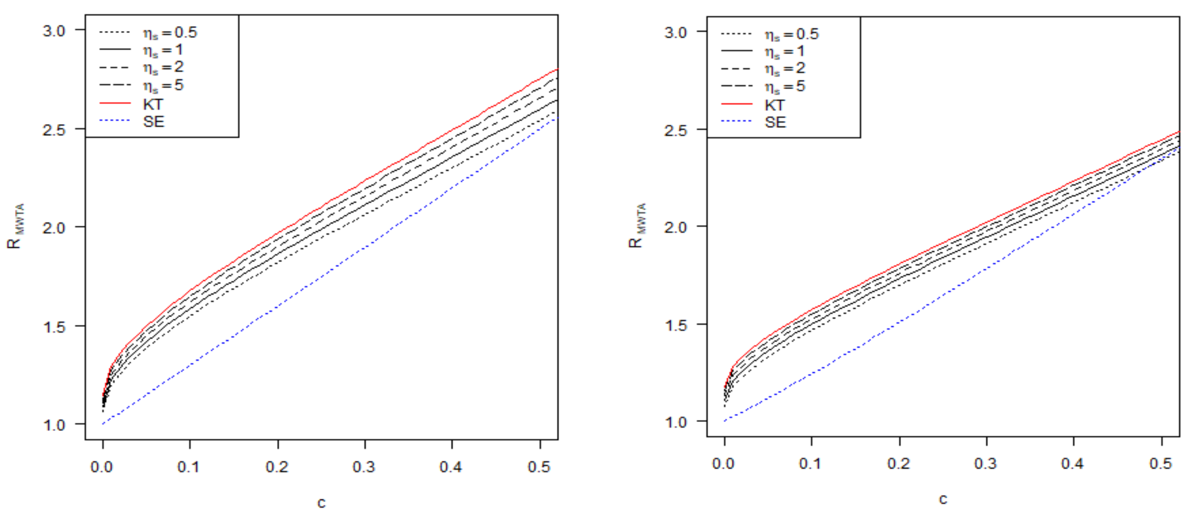

Figure A.3.1. The effects of the probability weighting for the shortage of market supply

Note: "KT" indicates a Kahneman-Tversky functional form ($\eta_s = +\infty$) and "SE" indicates a reference price switching effect. $\lambda = 2.25$ and $log\ \beta p_{t+1}/\beta E(p_{t+1})\sim N(0,0.20)$ are assumed in figures A.3.2

(a) the effect of η (b) the effect of λ

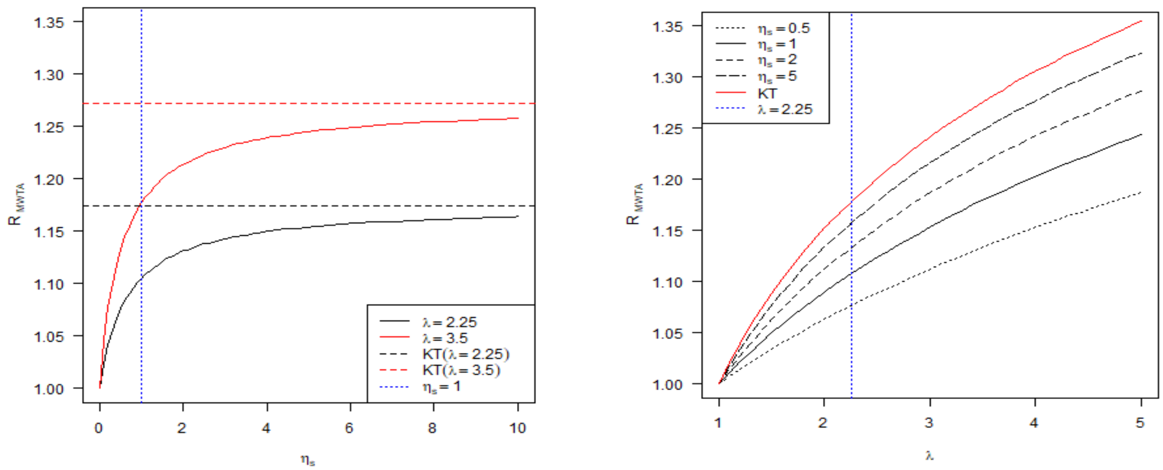

Figure A.3.2. The effect of loss aversion and reference dependence (truncated normal)

Note: η_s and λ are the parameters of loss aversion and reference dependence, respectively. "KT" indicates a Kahneman-Tversky functional form ($\eta_s = +\infty$). $log\ \beta p_{t+1}/\beta E(p_{t+1}) \sim N(0{,}0.20)$ is assumed in Figure A.3.2

(a) the effect of c (b) the effect of σ_ε (Std of $\frac{\beta p_{t+1}}{\beta E(p_{t+1})}$)

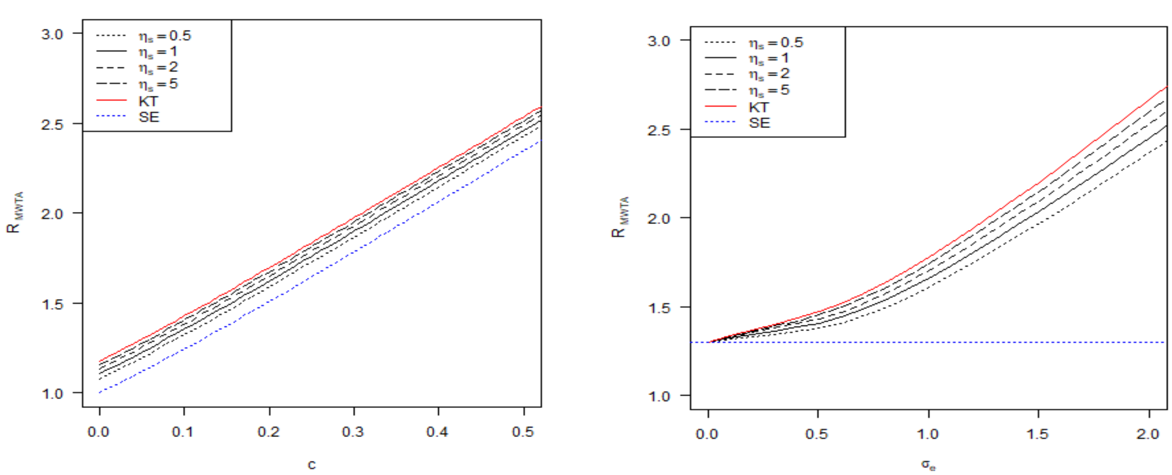

Figure A.3.3. The effect of reference switching and higher variance (truncated normal)

Note: c is the probability for the shortage of market supply in the future period. "KT" indicates a Kahneman-Tversky functional form ($\eta_s = +\infty$) and "SE" indicates a reference price switching effect. $\lambda = 2.25$. $log\ \beta p_{t+1}/\beta E(p_{t+1}) \sim N(0{,}0.20)$ is assumed in Figure A.3.3(a), and $c = C(S_{t+1} < \bar{S}_{t+1}) = 0.1$ is assumed in Figure A.3.3 (b).

(a) the effect of c (b) the effect of σ_ε (Std of $\frac{\beta p_{t+1}}{\beta E(p_{t+1})}$)

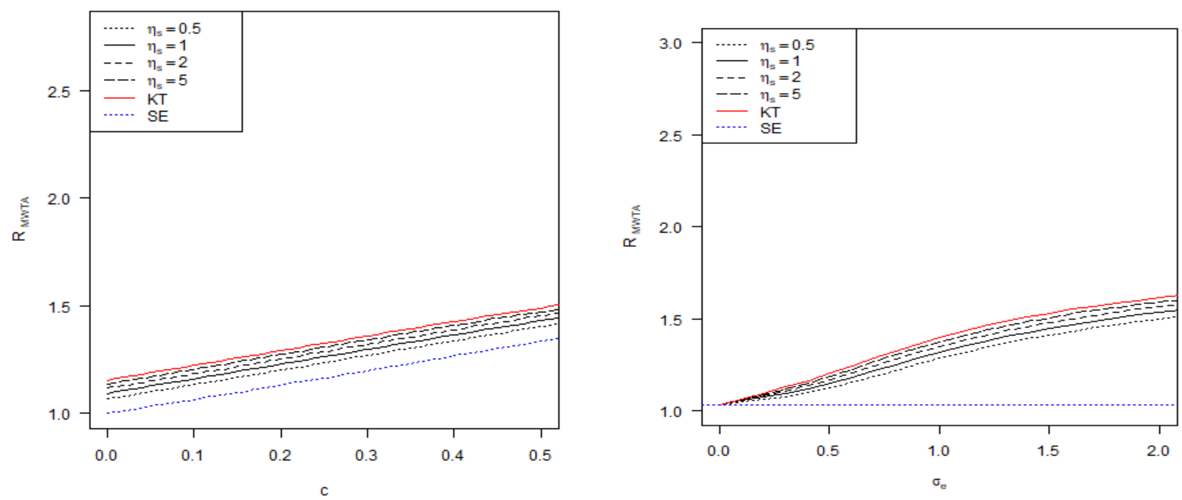

Figure A.3.4. The effect of the safety valve (truncated normal)

Note: c is the probability for the shortage of market supply in the future period. “KT” indicates a Kahneman-Tversky functional form ($\eta = +\infty$) and “SE” indicates a reference price switching effect. $\lambda = 2.25$. $log\, \beta p_{t+1}/\beta E(p_{t+1}) \sim N(0,0.20)$ is assumed in Figure A.3.4(a), and $c = C(S_{t+1} < \bar{S}_{t+1}) = 0.1$ is assumed in Figure A.3.4(b). For the price collar as a safety valve, the ceiling price ceiling and flooring price are assumed to be censored at the level of $R_{MWTA} = 2$ and $R_{MWTA} = 0.5$, respectively.

APPENDIX B

CHAPTER 2 APPENDIX

B.1. Supporting explanations

B.1.1. The procedures to obtain the Hurst exponent H through the DFA

i) Construct the cumulative sum X_t for the whole data series $\{x_t\}$ of size N as follows. For the DFA in our paper, we use price return series $\{r_t\}$ as $\{x_t\}$.

$$X_t = \sum_{i=1}^{t}(x_i - \bar{x}) \text{ where } \bar{x} \text{ is the mean of the time series} \quad \text{(B.1)}$$

ii) Divide X_t into segments of samples with j observations.

iii) For each segment, estimate the local trend $LT_t(j)$ using the least-square regression.

iv) Calculate the total error and the Fluctuation $F(j)$ through the root mean square error (RMSE) where

$$F(j) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(X_t - LT_t(j))^2}. \quad \text{(B.2)}$$

v) After repeating the previous steps for several other js and consequent segments, obtain several $F(j)$s for several js.

vi) After plotting the log-log graph of j against $F(j)$, the H value can be estimated as the slope of a straight-line fit using least-square regression.

B.1.2. Hall-Wood Estimator (Hall & Wood, 1993)

Hall-Wood estimator is a kind of box-count estimator considering small scales. Let $A(\varepsilon)$ be the total area of boxes at scale ε which intersects with the interpolation lines of time series $\{x_t\}$ (logarithmic KAU prices for the FD in our paper). Also, assume that time series is located at n regulary-spaced points. Then, at $\varepsilon_l = l/n$ where $l = 1,2,\cdots,n$, $A(l/n)$ can be estimated as follows

$$\hat{A}(l/n) = \frac{l}{n}\sum_{i=1}^{integer(n/l)}\left|x_{il/n} - x_{(i-1)l/n}\right|. \quad \text{(B.3)}$$

where $integer(n/l)$ is the integer part of n/l. Based on the least-square regression of $log\,\hat{A}(l/n)$ on $log(l/n)$, the Hall-Wood estimator $\widehat{D}_{HW}$ can be estimated as follows

$$\widehat{D}_{HW} = 2 - \left\{\sum_{l=1}^{L}(log\left(\frac{l}{n}\right) - \frac{1}{L}\sum_{l=1}^{L} log\left(\frac{l}{n}\right)) \cdot \hat{A}(l/n))\right\}\left\{\sum_{l=1}^{L}(log\left(\frac{l}{n}\right) - \frac{1}{L}\sum_{l=1}^{L} log\left(\frac{l}{n}\right))^2\right\}^{-1}. \quad \text{(B.4)}$$

where $L \geq 2$. As recommended by Hall & Wood (1993), if we use $L = 2$ to reduce potential bias, then we can obtain the Hall-Wood Estimator $\widehat{D}_{HW}$.

$$\widehat{D}_{HW} = 2 - \frac{log\left(\hat{A}\left(\frac{2}{n}\right)\right) - log\left(\hat{A}\left(\frac{l}{n}\right)\right)}{log\,(2)}. \quad \text{(B.5)}$$

B.1.3. Lanne-Nyberg GFEVD (2016) and Spillover Indices

Let's consider a k-dimensional nonlinear multivariate model including the linear VAR (p), using the framework of Pesaran and Shin (1998).

$$x_t = G(x_{t-1}, \cdots, x_{t-p}; \theta) + u_t \tag{B.6}$$

where u_t is i.i.d. and $G(\cdot)$ is a linear or non-linear function with the parameter vector θ. In our spillover analysis, the KAU price return ($r_t = log\, p_t - log\, p_{t-1}$) is used as x_t. Here, we focus on shocks hitting only one equation in x_t at a time and define the General Impulse Response Function (GIRF) of x_t to the shock δ_{jt} at time s as:

$$GI(v, \delta_{jt}, w_{t-1}) = E(x_{t+l} | u_{jt} = \delta_{jt}, w_{t-1}) - E(x_{t+l} | w_{t-1}), v = 0, 1, 2, \cdots, \tag{B.7}$$

where w_{t-1} is the history and δ_{jt} is the shock to the j-th equation that the expectations are conditioned on. Under the linear VAR model with the normality of u_t, the unscaled GIRF of the shock δ_j of u_t is

$$GI(v, \delta_{jt}, w_{t-1}) = A_v \Sigma s_j \sigma_{jj}^{-1} \delta_j \tag{B.8}$$

where Σ ($= \{\sigma_{ij}\}$) is the covariance matrix of the shock vector $\delta_j(= \sqrt{\sigma_{jj}})$, σ_{jj} is the jth diagonal element of Σ and s_j is a $k \times 1$ vector that its jth elements is 1 and otherwise 0.

Equation (B.7) can be interpreted as the time profile of the effect of the shock δ_{jt} at time t, which can be obtained by subtracting the expectations conditional on only the history from expectations conditional on both the shock and the history. Unlike the GFEVD from Pesaran and Shin, the Lanne-Nyberg GFEVD is constructed by using GIRF in equation (B.7) instead of the orthogonalized IRF in the GFEVD from Pesaran and Shin, which is not restricted to the linear VAR (p) with normally distributed errors. The components of Lanne-Nyberg GFEVD for time horizon h can be obtained by:

$$\lambda_{ij,w_{t-1}}(h) = \frac{\sum_{l=0}^{h} GI(v, \delta_{jt}, w_{t-1})_i^2}{\sum_{j=1}^{k} \sum_{l=0}^{h} GI(v, \delta_{jt}, w_{t-1})_i^2}, i, j = 1, \cdots, k \tag{B.9}$$

where j indicates the shock, i indicates the variable. The numerator implies the cumulative effect of the jth shock, while the denominator means the aggregate cumulative effect of all the shocks. Therefore, $\lambda_{ij,w_{t-1}}(h)$ implies the relative contribution of a shock to the jth equation with respect to the total effect of all k shocks on the ith variable in x_t after h period; here the sum of these contributions is equal to one, unlike DY variance decomposition.

Following Diebold and Yilmaz (2014), the "Total" spillover is obtained by:

$$S_{i,Total}^{LN}(h) = \frac{\sum_{i,j=1\ for\ i\neq j}^{k} \lambda_{ij,w_{t-1}}(h)}{\sum_{i,j=1}^{k} \lambda_{ij,w_{t-1}}(h)} \cdot 100 \tag{B.10}$$

which measures the contribution of spillovers of volatility shocks across all assets to the total forecast error variance. The directional spillover index from all other variable j to variable i ("To") and the MLNDY directional spillover index from variable i to all other variable j ("From") obtained by:

$$S_{i,To}^{LN}(h) = 100 \times \sum_{j=1\ for\ j\neq i}^{k} \lambda_{ij,w_{t-1}}(h) \text{ and}$$

$$S_{i,From}^{LN}(h) = 100 \times \sum_{j=1\ for\ j\neq i}^{k} \lambda_{ji,w_{t-1}}(h) \tag{B.11}$$

Using equation (B.11), the "Net" spillover index can be calculated as follows:

$$S_{i,Net}^{LN}(h) = S_{i,From}^{LN}(h) - S_{i,To}^{LN}(h) \tag{B.12}$$

Likewise, the "Net Pairwise" spillover index for each pair can be obtained by:

$$S_{ij,pair}^{LN}(h) = \left(\frac{\lambda_{ij,w_{t-1}}(h)}{\sum_{m=1}^{k} \lambda_{im,w_{t-1}}(h)} - \frac{\lambda_{ji,w_{t-1}}(h)}{\sum_{m=1}^{k} \lambda_{jm,w_{t-1}}(h)}\right) \cdot 100 \tag{B.13}$$

B.2. Supporting tables and figures

Table B.2.1. Descriptive statistics of daily KAU, Dubai Oil, and Kospi200 returns

	KAU	**Oil**	**Kospi200**
observations	1117	1117	1117
mean	0.119	-0.058	0.004
median	0.000	0.000	0.054
max	9.531	35.146	8.755
min	-10.536	-39.065	-7.978
std.dev.	1.735	3.098	1.054
skewness	-0.782	-0.476	-0.198
surtosis	21.015	49.164	11.426
ADF test	-18.367***	-4.215***	-8.437***
PP test	-28.693***	-32.969***	-34.563***
J-B	15218***	112536***	6084***

Note: The Augmented Dickey-Fuller (ADF) and the Phillips-Perron (PP) test a null hypothesis of a unit root (non-stationarity) in the equation with constant and time trend. J-B refers to the statistics of the Jarque-Bera test for normality. *, ** and *** are significant at 10%, 5%, and 1% level, respectively.

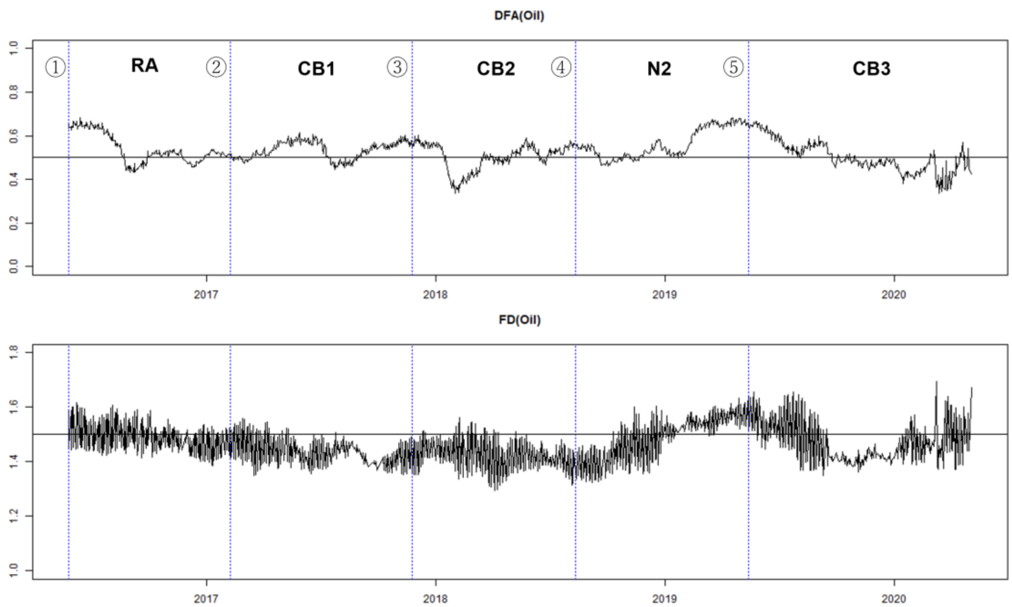

Figure B.2.1. Time-varying Hurst exponent and Fractal dimension (Hall-Wood) of Dubai Oil price

Note: The sample period is from October 7, 2015 to May 4, 2020. Black horizontal lines indicate $H = 0.5$ (in the top panel) and $\widehat{D}_{HW} = 1.5$ (in the bottom panel). Blue dotted vertical lines indicate important event days (①, ②, ③, ④, and ⑤) in Figure 2.3.

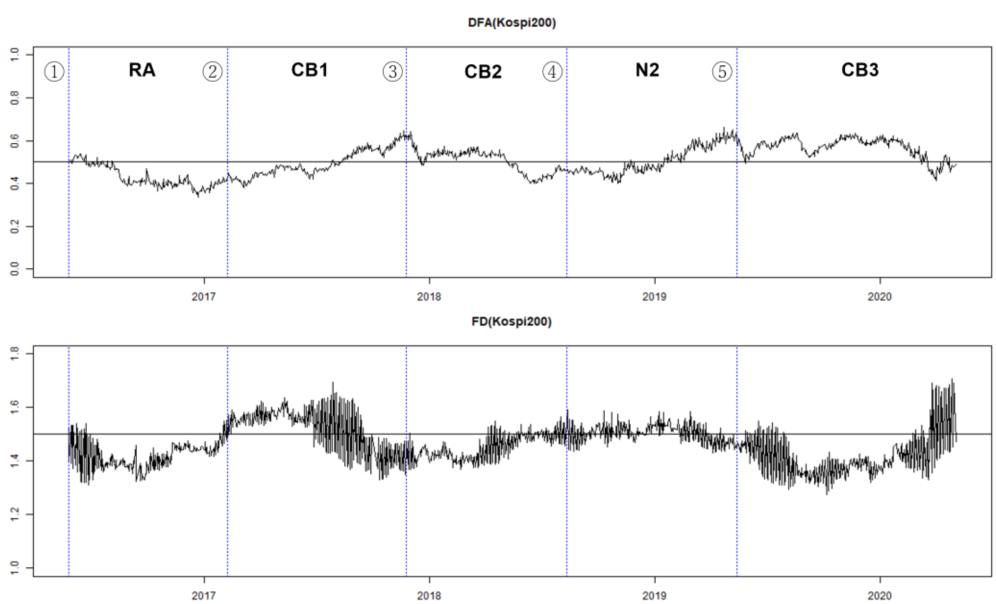

Figure B.2.2. Time-varying Hurst exponent and Fractal dimension (Hall-Wood) of Kospi200 index

Note: The sample period is from October 7, 2015 to May 4, 2020. Black horizontal lines indicate $H = 0.5$ (in the top panel) and $\widehat{D}_{HW} = 1.5$ (in the bottom panel). Blue dotted vertical lines indicate important event days (①, ②, ③, ④, and ⑤) in Figure 2.3.

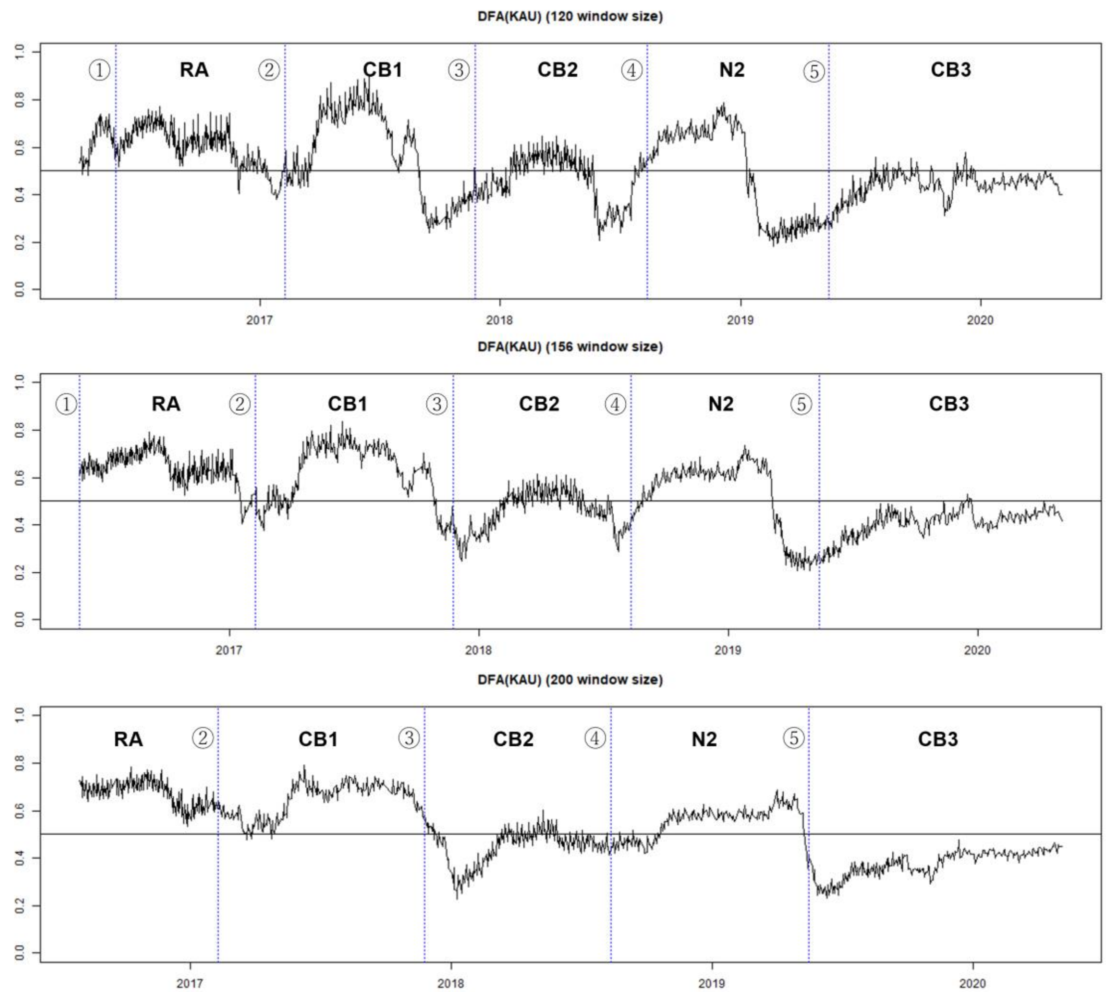

Figure B.2.3. Time-varying Hurst exponent of KAU returns with different window sizes

Note: The sample period is from October 7, 2015 to May 4, 2020. Black horizontal lines indicate $H = 0.5$. Blue dotted vertical lines indicate important event days (①, ②, ③, ④, and ⑤) in Figure 2.3.

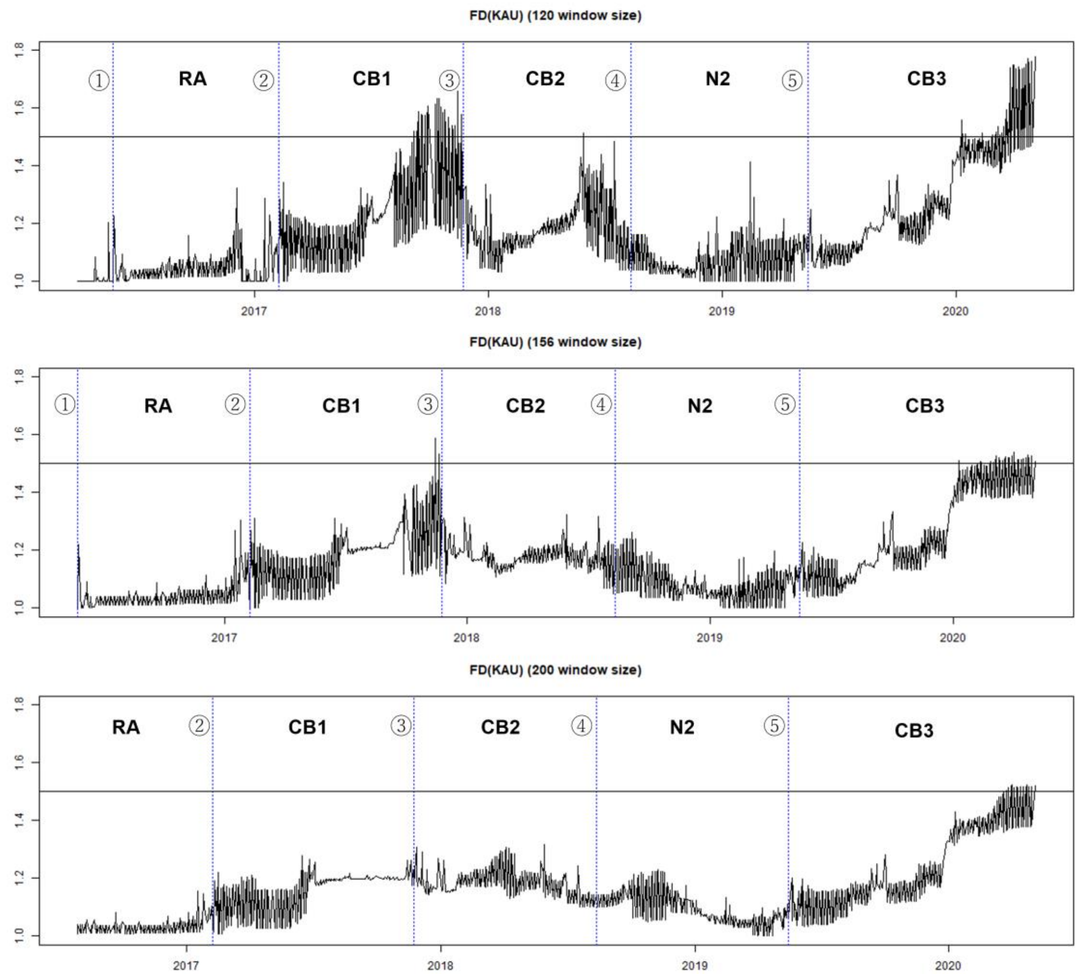

Figure B.2.4. Time-varying Fractal dimension (Hall-Wood) of KAU prices with different window sizes

Note: The sample period is from October 7, 2015 to May 4, 2020. Black horizontal lines indicate $\widehat{D}_{HW} = 1.5$. Blue dotted vertical lines indicate important event days (①, ②, ③, ④, and ⑤) in Figure 2.3.

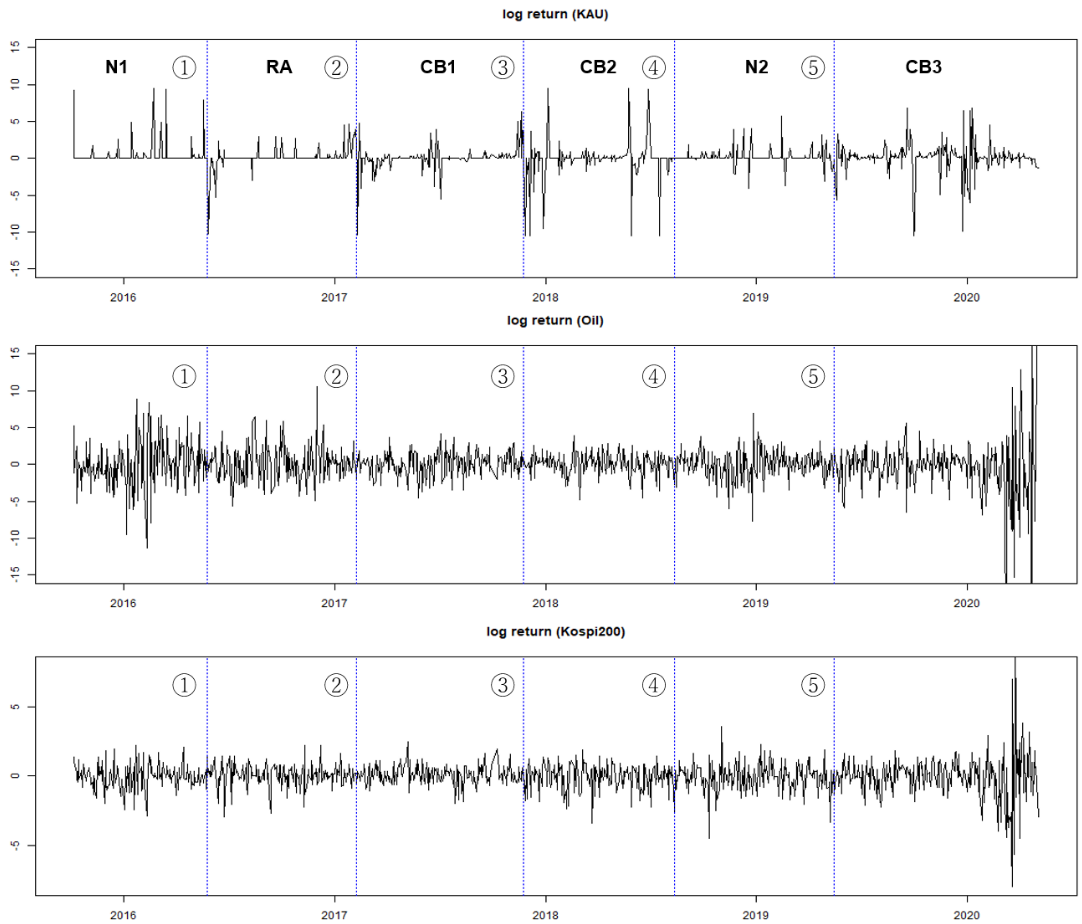

Figure B.2.5. Changes in daily KAU, Dubai Oil, and Kospi200 returns

Note: The sample period is from October 7, 2015 to May 4, 2020. Blue dotted vertical lines indicate important event days (①, ②, ③, ④, and ⑤) in Figure 2.3.

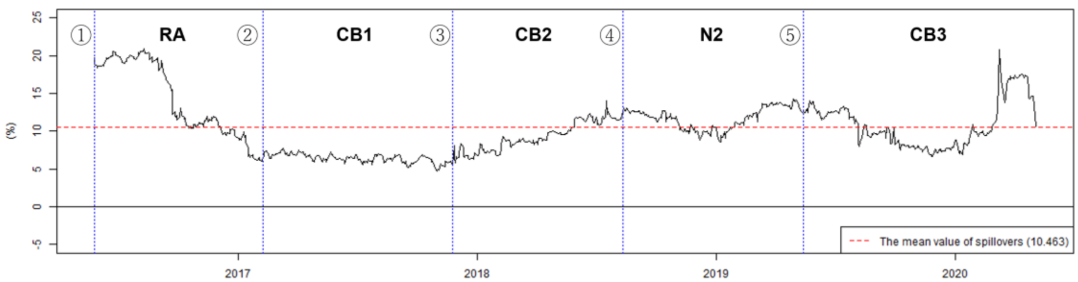

Figure B.2.6. The total spillovers among returns of KAU, Dubai oil price, and Kospi200 Index

Note: The sample period is from October 7, 2015 to May 4, 2020. Blue dotted vertical lines indicate important event days (①, ②, ③, ④, and ⑤) in Figure 2.3.

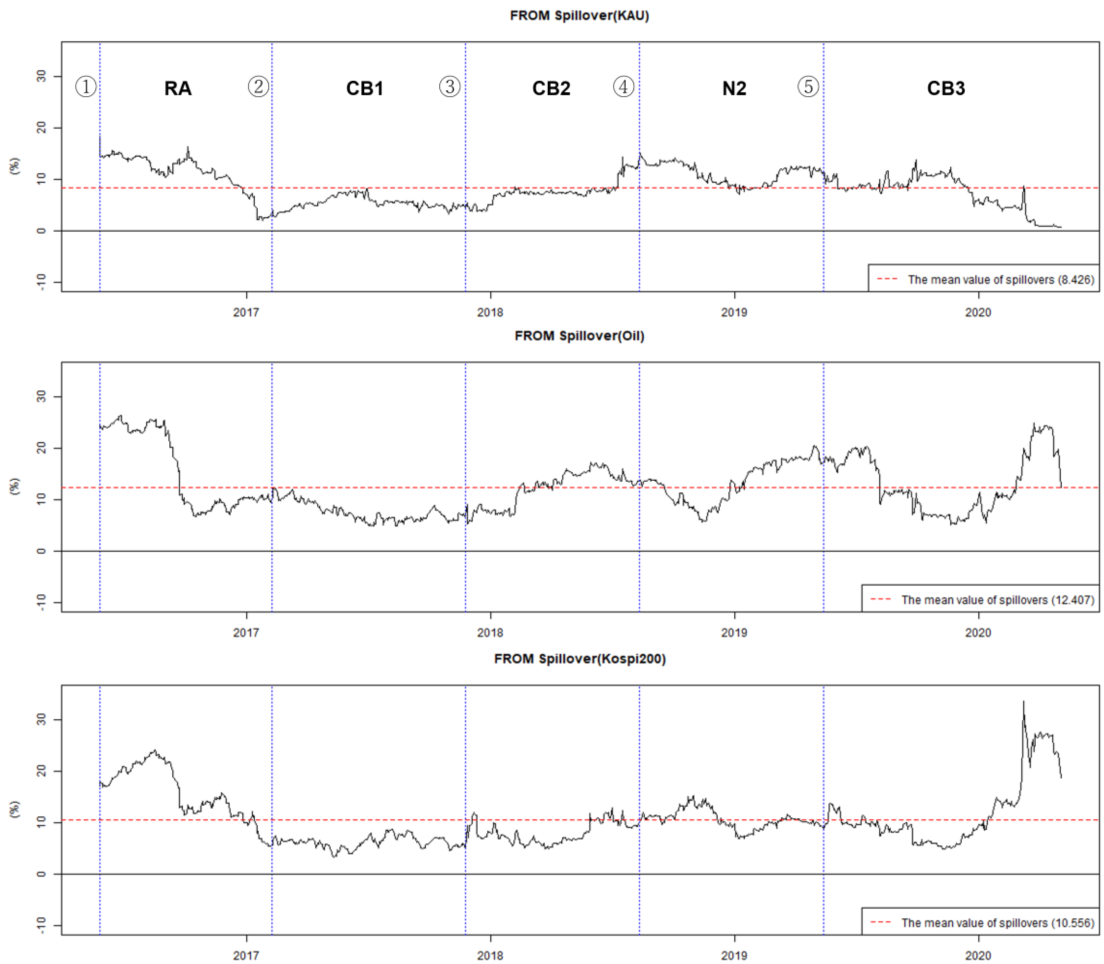

Figure B.2.7. The from spillovers among returns of KAU, Dubai oil price, and Kospi200 Index.

Note: The sample period is from October 7, 2015 to May 4, 2020. Blue dotted vertical lines indicate important event days (①, ②, ③, ④, and ⑤) in Figure 2.3.

APPENDIX C

CHAPTER 3 APPENDIX

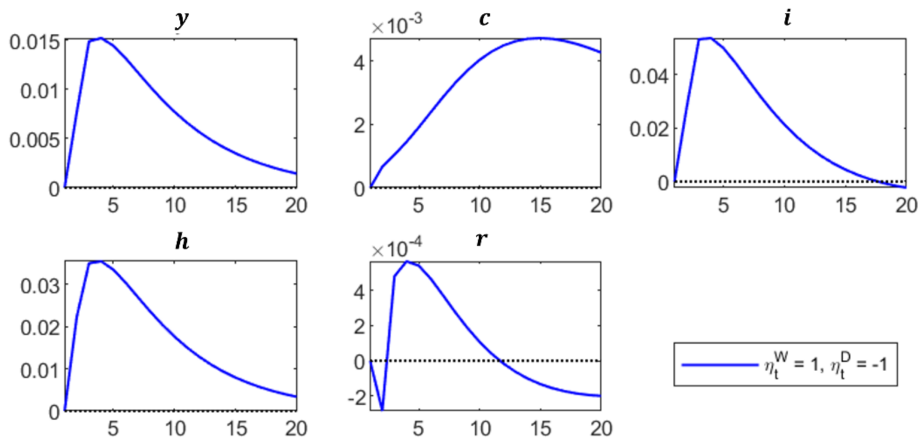

Figure C.1. IRF of macro variables with a standard weather shock.

Note: IRFs reports percentage deviations from the steady state of each variable after a standard weather shock ($\eta_t^W = 1, \eta_t^D = -1$).

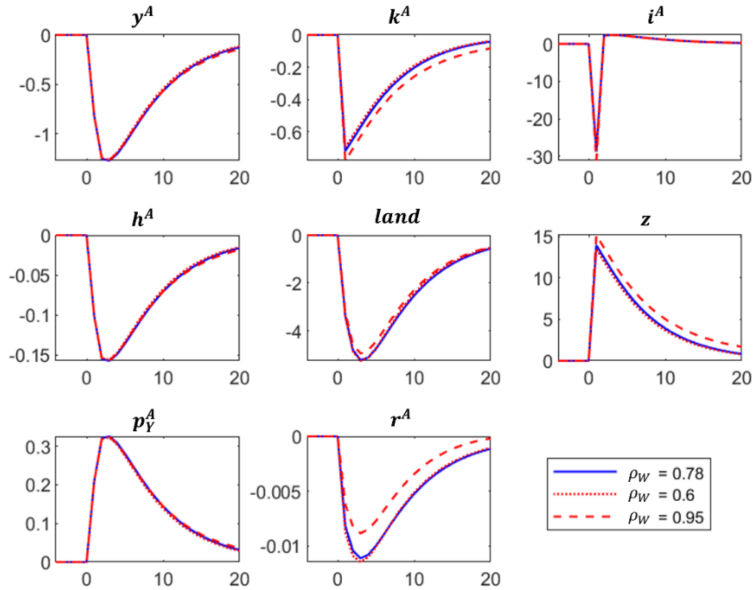

Figure C.2. IRFs for different values of the parameter ρ_W after a standard weather shock

Note: IRFs reports percentage deviations from the steady state of each variable after a standard weather shock ($\eta_t^W = 1, \eta_t^D = -1$) at $t = 1$. The blue solid line indicates the IRF under the estimated parameter in our model.

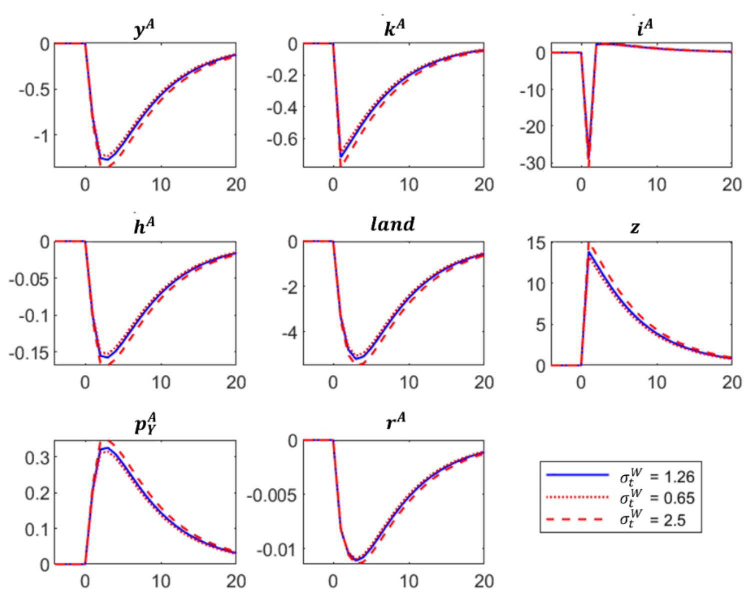

Figure C.3. IRFs for different values of the parameter σ_W after a standard weather shock

Note: IRFs reports percentage deviations from the steady state of each variable after a standard weather shock ($\eta_t^W = 1, \eta_t^D = -1$) at $t = 1$. The blue solid line indicates the IRF under the estimated parameter in our model.