

Cross-Commodity Futures Portfolios as Tools for Environmental Risk Management: Evidence from Tail Risk and Regime Dependence

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Abstract: Environmental risks, including climate variability, resource scarcity, and policy changes, have increased uncertainty and price volatility across global commodity markets. Although a growing body of literature has examined commodity price dynamics, spillovers, and cross-market dependence, relatively fewer studies integrate cross-commodity dependence, downside tail risk, and regime-sensitive portfolio construction within a unified environmental risk management framework. This study evaluates whether cross-commodity futures portfolios can serve as tools for resource-price risk management under environmental and market uncertainty. Using a comprehensive dataset covering energy, agricultural, metal, and livestock futures, the analysis combines conditional value-at-risk (CVaR), rolling correlation analysis, principal component analysis, and regime-based portfolio evaluation. Hierarchical risk parity (HRP) and CVaR-minimizing portfolios are evaluated under both low-risk and high-risk market regimes. The results show that risk-oriented portfolio strategies substantially reduce volatility, downside tail risk, and maximum drawdown relative to an equal-weighted benchmark. The dependence analysis further indicates that energy markets constitute the dominant common factor driving cross-commodity risk transmission. Regime analysis and state-space estimation reveal that systemic commodity risk evolves dynamically and becomes more pronounced during periods of elevated market stress. Overall, the findings suggest that commodity-based financial indicators can complement traditional environmental monitoring by providing market-based information on evolving systemic risk under environmental and market uncertainty.

Keywords: environmental uncertainty; commodity futures; tail risk; cross-commodity dependence; portfolio-based risk management; regime dynamics

1. Introduction

Resource markets play a fundamental role in the global economy and are increasingly influenced by environmental and market uncertainty [1,2]. Climate variability, resource scarcity, policy interventions, and supply-chain disruptions have contributed to greater price volatility across energy, agricultural, metal, and livestock markets [1,3]. These developments have increased concerns about how uncertainty propagates across interconnected commodity markets and how financial risk-management strategies can improve the resilience of resource-dependent economic systems [4]. Rather than directly measuring environmental conditions, this study examines market-based manifestations of environmental and market uncertainty through commodity-price volatility, downside tail risk, and cross-commodity dependence.



Commodity markets are increasingly interconnected through production linkages, substitution effects, global trade, and financial investment [5,6]. Environmental and economic shocks therefore rarely affect individual commodities in isolation; instead, they often propagate across commodity categories through common demand conditions, supply-chain interactions, and market expectations [7–9]. Accordingly, a growing literature has examined cross-commodity dependence, volatility spillovers, and systemic commodity risk [10]. However, relatively fewer studies integrate downside tail-risk measurement, regime-dependent market dynamics, and portfolio-based risk management within a unified resource-price risk management framework [11,12].

Commodity futures markets incorporate market expectations regarding future supply conditions, demand prospects, and uncertainty [3,13]. Consequently, futures prices offer a useful financial perspective for assessing resource-price risk under environmental and market uncertainty. An important question is whether cross-commodity diversification remains effective when volatility and dependence increase simultaneously [14]. Although portfolio diversification is generally expected to reduce risk, its effectiveness may weaken during periods of elevated market stress because correlations across commodities tend to strengthen [15].

To address this research gap, this study combines cross-commodity dependence analysis, downside tail-risk measurement, regime classification, and portfolio evaluation. Instead of emphasizing return maximization, the proposed framework focuses on resource-price risk management under environmental and market uncertainty. Using futures data covering major commodity categories, the study evaluates whether risk-oriented portfolio strategies can enhance resilience under different market conditions.

The analysis further incorporates a regime-based perspective to examine whether commodity-market dependence and portfolio performance differ between relatively low-risk and high-risk market environments [11]. Changes in volatility and cross-commodity dependence may alter diversification effectiveness, making adaptive portfolio strategies more appropriate than static risk-allocation approaches [16,17].

This study contributes in four respects. First, it documents heterogeneity in downside tail risk across major commodity categories. Second, it integrates dependence analysis, regime classification, and portfolio evaluation within a unified resource-price risk management framework. Third, it applies a state-space smoothing framework to characterize the dynamic evolution of a common market-risk indicator derived from principal component analysis. Fourth, it provides evidence on the effectiveness of risk-oriented portfolio allocation under different market conditions.

By integrating commodity futures analysis with resource-price risk management under environmental and market uncertainty, this study contributes to the growing intersection of ecological economics, finance, and sustainability. Although the analysis is based on financial market information rather than direct environmental observations, the findings suggest that commodity-based financial indicators can complement traditional environmental and economic risk-monitoring approaches to monitoring resource-related risks. The results provide useful implications for policymakers, institutional investors, and resource-dependent firms seeking to strengthen resilience under increasing environmental and economic uncertainty.

2. Literature Review and Conceptual Background

2.1. Environmental Uncertainty and Commodity Price Risk

The unpredictability of commodity markets is closely linked to various sources of uncertainty. Changes in energy market conditions, environmental pressures, and broader economic disturbances may affect resource-market dynamics and alter the balance between supply and demand [1,4,18]. Historical evidence also shows that major oil shocks can trigger persistent volatility and structural adjustments across commodity markets [19].

Agricultural commodities are especially impacted by climate variability and extreme weather due to their sensitivity to temperature, precipitation, and soil conditions [20,21]. Such increases in food prices and price volatility may also contribute to social unrest, illustrating the broader socioeconomic consequences of agricultural commodity risk [22]. On the other hand, environmental regulations, restrictions related to the extraction sector, and new policies related to the energy transition are major factors affecting the energy and metal markets [1,23]. As a result of the impact of environmental factors, price risks in commodities are not uniform.

Recent research has shown financial-market manifestations of resource-related uncertainty cause non-linear changes in prices that are riskier than standard theories would show [21,24]. These findings demonstrate the importance of applying tail risk analysis in the commodities market. Environmental issues impact the price of commodities; thus, metrics that analyze the extremes of risk debts, such as Conditional Value at Risk (CVaR), are the most applicable [12].

Recent empirical studies have shown that, especially in the case of agricultural and energy markets, the impact of climate risk and environmental concern are increasingly becoming apparent in commodity price behavior

[20,25,26]. These studies collectively suggest the importance of the undertaking of risk measures to environmental uncertainty and the ability to capture the diverse exposures of the different categories of resources.

2.2. Cross-Commodity Dependence and Systemic Resource Risk

While the analysis by commodity is still important, the markets of resources have reached a point of utmost interdependence. Environmental and economic shocks are transmitted to different commodities through substitution, shared production inputs, and global supply chains [9,16]. Thus, shocks originating in one segment of the resource ecosystem may cause price cooperation in other segments, increasing systemic risk [7,8].

There are even more widespread economic and environmental impacts on the global resource markets. Energy prices have the most impacts on the extraction, processing, transportation, and storage of agricultural and metal commodities. Energy markets are especially significant in agricultural and metal commodity markets. Recent empirical studies have shown that energy price shocks precede significant price changes in other commodity markets [27]. Energy markets therefore often play a central role in transmitting shocks across commodity markets.

There is a common finding in studies of important systemic shocks that commodity price correlations rise, and the risk reducing correlations decrease, during periods of extreme market risk [10,15]. Recent studies on the interconnectedness of markets and the network analysis of risky and causal factors, as well as, the impact of extreme rare shocks to the system have shown the increasing interconnectedness of commodity markets. These extremes are the impact of macro-economic uncertainty, policy shifts, and environmental stress factors [7–9]. Correlations among commodity markets often strengthen during crisis periods, reducing the effectiveness of diversification strategies [5,10].

From a resource governance perspective, such dependence can mean that environmental disturbances can produce cascading effects through the different types of resources. Hence, cross-commodity dependence is crucial for the assessment of systemic resource risk and for the formulation of effective risk mitigation measures. Recent studies also emphasize the network structure and spillover dynamics of interconnected commodity markets [7].

2.3. Financial Instruments and Risk Management in Environmental Contexts

Futures markets are important because they give participants the option to hedge against losses due to changes in the price of commodities [14,28]. Futures contracts help to reduce the risk in resource-dependent sectors by stabilizing the costs and revenues [28].

Under environmental and market uncertainty, commodity futures prices may reflect changing expectations regarding climate risk, policy developments, and supply conditions [20,25]. Therefore, these contracts can be market-based indicators of resource-price risk under environmental and market uncertainty [29]. Recent research observes that climate risk and changes in policy can cause higher volatility of commodity futures, especially in the energy and agriculture sectors [24,25,29].

The majority of commodity futures research assumes that the goal of participants is to either maximize the expected returns [13,28]. However, within the framework of environmental finance, these contracts are risk instruments more than earning instruments. Therefore, risk-related portfolio strategies that look to the reduction of volatility and tail risk, are likely to be more valuable to institutional investors, public funds, and firms that are subject to environmental risk [12,14]. More broadly, the risk-management literature shows that downside-risk constraints can materially affect optimal portfolio policies and asset prices [30]. Tail-risk spillovers are particularly evident among agricultural commodity futures, suggesting that downside risk can propagate rapidly through interconnected food markets [31]. Carbon-related financial risks have also become increasingly important in commodity and resource markets [23].

The significance of these strategies is still an unresolved topic. Research indicates that the benefits of portfolio risk management, in the commodity markets, may be further weakened as the correlation of the commodities increases during market distress. Therefore, more attention is warranted to address the extreme risk of systems and the tail risk [32].

2.4. Regime Dependence and Research Gap

Some studies argue that the financial and commodity markets exhibit dependent regimes in which there is both time of relative stability and time that the markets are dependent and volatile [11,33]. The presence of a stressing regime in the markets is associated with a higher degree of correlation, a greater likelihood of events in the last risky segment, and a lower degree of diversification [10,15].

The impact of the environment, together with the process of the energy transition, and climate change policies, may alter the trajectories of commodities and affect the structure and relationships of markets [1,21]. The dependence of climate and policies has a significant impact on the dependence of resource markets, and a regime-sensitive analysis is critical [1,11].

Despite these advances, existing studies typically examine commodity spillovers, portfolio allocation, or climate-related risks separately. Less attention has been paid to integrating these perspectives into a unified framework linking environmental uncertainty, systemic commodity risk, and portfolio-based buffering strategies. This study addresses these gaps by adopting a comprehensive, risk-oriented, and regime-sensitive framework. By combining tail-risk measures, cross-commodity dependence analysis, and regime-based assessment, the paper evaluates whether diversified commodity futures portfolios can serve as effective tools for environmental risk management under varying market conditions.

The study aims to reduce the ambiguity in the relationships among the environmental factors, shocks and risks associated with dependencies of commodities, and risk management within a framework that covers three significant elements, as depicted in Figure 1. The elements are resource-related uncertainty, cross-commodity dependencies, and risk management focused on portfolios.

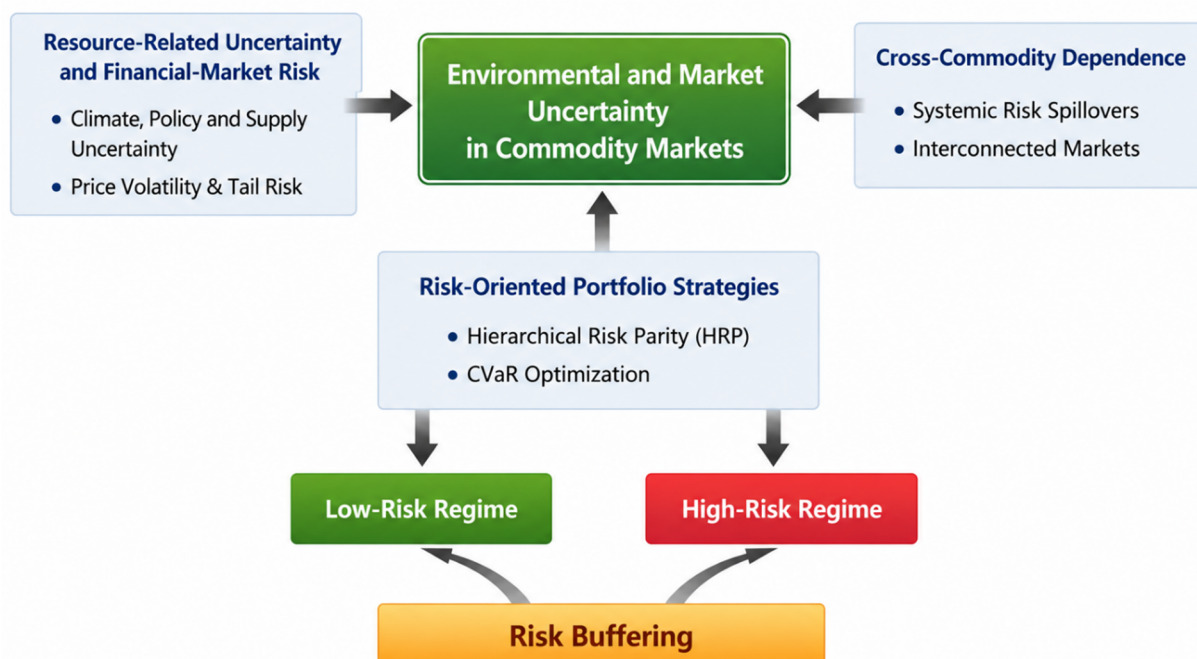


Figure 1. Conceptual framework.

The framework suggests that resource-related uncertainty, including climate and policy alterations, result in greater tail risk and volatility in commodity markets. The framework recognizes that the energy markets are the primary means in which the risks commodities are focused, and therefore, the cross-commodity dependencies increase during a stress regime. The study assesses the environmental risk that diversified portfolios of commodity futures may mitigate during a variety of market conditions by applying HRP combined with CVaR strategies.

There has been an increased interest in cross-commodity risks within the literature. However, there are very few papers that incorporate regime-based risk analysis, tail-risk metrics, and portfolio optimization in relation to multiple commodity groups. In addressing this gap, the paper attempts to integrate portfolio strategies in different market regimes with tailrisk metrics (CVaR) to enhance management of environmental risks in commodities.

3. Methodology

The methodological framework integrates risk measurement, dependence analysis, and portfolio construction to assess the role of cross-commodity futures portfolios in environmental risk management. By combining volatility and tail-risk metrics with cross-resource dependence analysis and regime-based evaluation, the study offers a comprehensive approach to understanding how financial instruments can contribute to managing environmental and resource-related risks in commodity markets.

3.1. Data Sources and Preprocessing

This study employs a comprehensive dataset of commodity futures prices to examine risk characteristics and cross-commodity interactions under environmental uncertainty. The analysis focuses on daily futures price dynamics across multiple resource categories in order to capture heterogeneous risk exposure and systemic dependence within commodity markets.

The commodity futures data are obtained from the Commodities Futures Collection dataset available on Kaggle. This dataset consolidates futures price series across multiple resource categories, including animal products, agricultural commodities, fuels and energy, precious metals, and grains and cereals. A unified file (all_commodities_futures_collection.csv) provides an integrated view of all commodities with categorical identifiers, while individual files for each commodity are also available for detailed analysis. The data are publicly accessible at: <https://www.kaggle.com/datasets/guillemsverra/commodities-futures-collection> (accessed on 30 April 2026). The category labels provided in the dataset are used to classify commodities into broad resource groups for cross-category risk analysis. The sample includes widely followed futures contracts across energy, agricultural, metal, and livestock categories. Contracts with insufficient historical observations were excluded. Continuous adjusted price series were used to improve comparability across maturities.

Daily closing prices are used to construct logarithmic returns for each commodity, defined as: $r_{i,t} = \ln(P_{i,t} / P_{i,t-1})$, where $P_{i,t}$ denotes the closing price of commodity i at time t . Commodities with insufficient observations or discontinuous price series are excluded to ensure robustness and comparability across resource categories.

Commodity classification information is retained throughout the analysis to distinguish between energy-related resources, agricultural and grain commodities, and precious metals. This classification allows the study to examine both within-category risk characteristics and cross-category systemic interactions. All return series are aligned by date, and missing observations are handled through listwise deletion to preserve the integrity of time-series relationships.

3.2. Measuring Resource Price Risk and Environmental Uncertainty

In the context of environmental risk management, this study interprets extreme price volatility and tail risk in commodity futures markets as financial manifestations of environmental and resource-related uncertainty. Climate variability, supply disruptions, and resource scarcity are often reflected in futures prices through heightened volatility and extreme movements.

To quantify price risk, two complementary measures are employed. First, rolling volatility is calculated over a fixed window to capture time-varying price instability. Second, conditional value-at-risk (CVaR) is used to measure downside tail risk. CVaR is defined as the expected loss given that returns fall below a specified quantile of the return distribution. Unlike variance-based measures, CVaR focuses explicitly on extreme adverse outcomes, making it particularly suitable for assessing risks associated with financial-market manifestations of resource-related uncertainty.

By comparing volatility and CVaR across commodities and categories, the analysis identifies heterogeneity in risk exposure and highlights which resource markets are more vulnerable to extreme price movements. The objective of the analysis is not to forecast prices or maximize returns, but to evaluate risk characteristics and buffering mechanisms under environmental uncertainty.

3.3. Cross-Commodity Dependence and Systemic Risk Analysis

The study identifies correlation-based and factor-based approaches to examine the cross-commodity dependence structures and the transmission of systemic risk across resource markets. The study uses rolling correlation matrices to represent the dynamics of the dependencies of commodity returns to determine the periods of time when the correlation signals systemic risk and diminishes the degree of diversification [34]. To determine the extent to which commodity price returns are influenced by systemic risk and not by some shocks that are caused by other sources, the study conducted principal component analysis (PCA) on the returns to determine the underlying commodity price risk [35]. Finally, the PCA factor loadings determine how each resource impacted the commodity risk. Ultimately, the factor and correlation analysis provides understanding of the cross-commodity risk linkage structures and of the extent to which the energy commodities are the primary catalysts of systemic price risk.

To describe the time-varying evolution of the dominant common factor, this study further applies a simple state-space smoothing framework to the first principal component. In this specification, PC1 is treated as the

observed series summarizing common variation across commodity returns, while the latent state is estimated through the Kalman filter. Given the absence of additional structural environmental, macroeconomic, or policy variables, the estimated state is interpreted as a smoothed market-based common-risk indicator rather than as an independently identified environmental-risk factor.

This study combines the powerful feature of state-space modeling with the principal components' analysis of primary commodities to bridge the gap between the static identification of systemic risk components and the dynamic structural changes of the market, thereby providing a closer and continuous representation of the systemic risk rather than the rather approximated point in time or average cumulative systemic risk.

3.4. Portfolio Construction for Environmental Risk Management

Rather than focusing on return maximization, this study constructs commodity futures portfolios explicitly as tools for environmental risk management. The objective is to evaluate whether diversified exposure across resource categories can mitigate extreme price risks associated with environmental uncertainty. Portfolios are rebalanced monthly using recursively estimated weights based on a rolling historical estimation window. Transaction costs are not incorporated and are discussed as a limitation.

Two risk-based portfolio construction methods are employed. First, the hierarchical risk parity (HRP) approach is used to allocate portfolio weights based on the hierarchical clustering of asset correlations [17,32]. HRP does not rely on expected return estimates and is robust to estimation errors in covariance matrices, making it well suited for multi-commodity portfolios characterized by complex dependence structures.

Second, a CVaR-minimizing portfolio is constructed with an explicit focus on minimizing downside tail risk, in order to assess their potential role as risk-buffering instruments. This approach directly targets extreme losses and aligns with the study's emphasis on risk buffering rather than performance enhancement.

Benchmark portfolios, including equal-weighted allocations, are constructed for comparison. Portfolio performance is evaluated using risk-oriented metrics such as volatility, CVaR, and maximum drawdown [12,36]. This comparative framework allows the assessment of whether risk-based diversification across commodity categories enhances portfolio stability under adverse conditions.

3.5. Regime-Based and State-Space Risk Assessment

To capture structural changes in commodity market dynamics, the study adopts a two-layer framework combining discrete regime classification with continuous systemic risk estimation. First, an unsupervised clustering procedure is applied using rolling market volatility and average pairwise correlation to classify observations into relatively lower-risk and higher-risk market regimes. Second, a state-space model is used to estimate a latent systemic commodity risk factor. The observation equation links the first principal component of commodity returns to the latent state, while the state equation models its stochastic evolution over time. Estimation is conducted using the Kalman filter [37].

The combination of regime classification and state-space modeling enables the analysis to distinguish between abrupt regime shifts and gradual changes in underlying risk conditions. While regime labels capture discrete transitions between stable and stress states, the latent risk factor reflects the accumulation and dissipation of systemic pressure over time. This integrated framework allows for a more nuanced assessment of whether risk characteristics and diversification effects differ across market states and how systemic risk evolves prior to and during periods of elevated volatility and correlation.

4. Results

4.1. Risk Heterogeneity across Resource Categories

This section examines heterogeneity in resource price risk across commodities using tail-risk and volatility measures. Figure 2 reports CVaR (95%) by ticker, colored by commodity category. The results reveal substantial cross-commodity heterogeneity in downside tail risk, indicating that environmental and supply-related uncertainty is not uniformly distributed across resource markets.

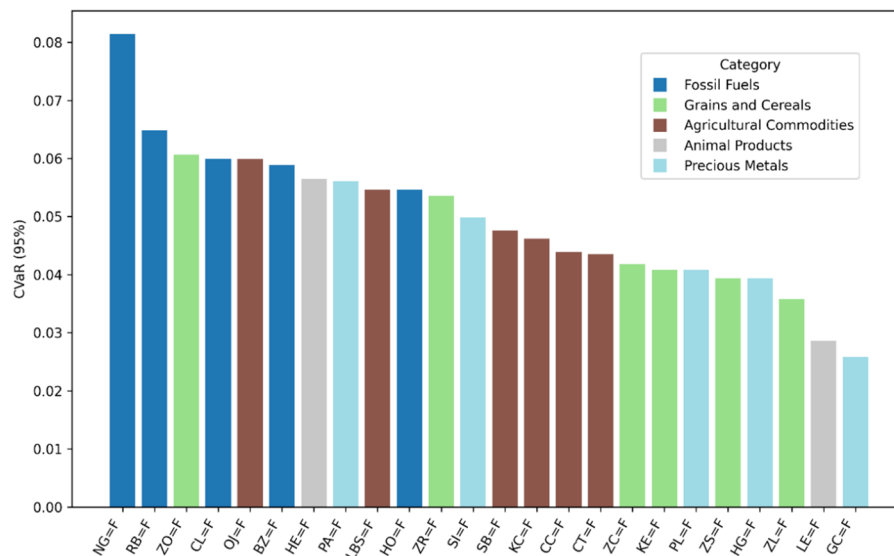


Figure 2. Commodity futures tail risk (CVaR 95%) by Ticker (colored by category).

The results indicate substantial heterogeneity in downside risk across commodity futures markets. Energy-related commodities are characterized by markedly higher tail risk and volatility, suggesting greater exposure to extreme price movements that may reflect underlying environmental, supply-side, and systemic uncertainties. In contrast, several metal and livestock contracts exhibit comparatively lower tail risk, implying a more stabilizing role within the broader resource system. At the same time, several agricultural contracts also display non-negligible tail risk, suggesting that climate and supply-side vulnerabilities can translate into pronounced downside outcomes in food-related markets. Overall, the dispersion in CVaR across categories supports the need for cross-resource risk management rather than single-commodity risk assessment.

4.2. Cross-Commodity Dependence and Common Factors

To evaluate systemic risk transmission and common drivers across resource markets, we analyze dependence structures using rolling correlations and PCA. Figure 3 presents the explained variance ratios of the first three principal components. The first component alone explains a non-trivial share of total variance, implying the existence of a dominant common factor affecting multiple resource categories.

Figure 4 further reports PC1 loadings, showing that the common factor is largely driven by energy-related futures. This pattern indicates that energy markets can serve as a central channel of systemic influence, amplifying cross-market co-movements. Such a dependence structure is consistent with the view that energy price uncertainty can propagate across broader resource systems, affecting commodities that are linked through production costs, transportation, and broader macro-environmental conditions.

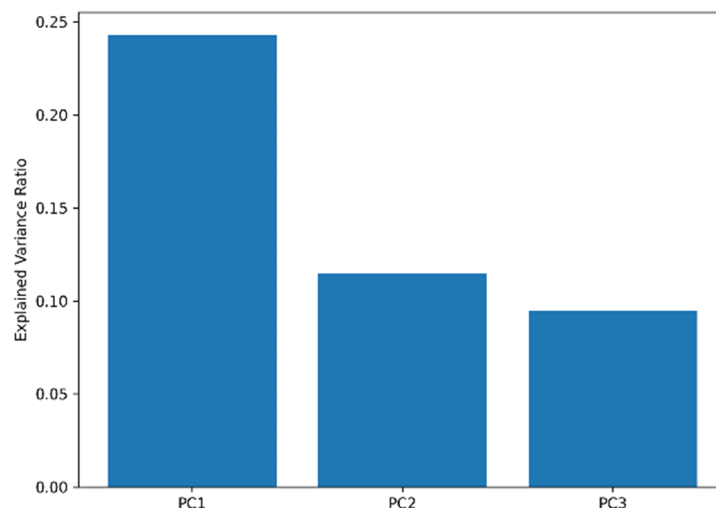


Figure 3. PCA explained variance (PC1–PC3).

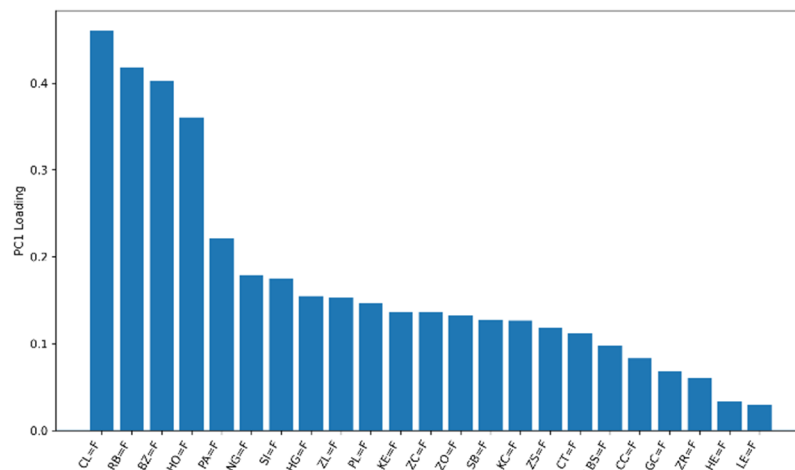


Figure 4. PC1 loadings by Ticker.

4.3. Portfolio-Based Buffering Effect under Environmental Uncertainty

This study constructs cross-commodity futures portfolios as tools for environmental risk management. Rather than targeting return maximization, the portfolios are evaluated primarily by their risk buffering capacity. Table 1 compares the equal-weight benchmark (EQ), the hierarchical risk parity portfolio (HRP), and the CVaR-minimizing portfolio (CVaRmin).

Table 1. Comparison of portfolio risk measures.

Portfolio	Annualized Volatility	CVaR (95%)	Max Drawdown (log)
EQ	0.1438	0.0220	−0.7722
HRP	0.1156	0.0177	−0.5914
CVaRmin	0.1000	0.0149	−0.3683

Note: Annualized volatility is calculated from daily portfolio returns. CVaR(95%) is reported at the daily frequency. Maximum drawdown is calculated from cumulative log returns over the full sample period.

The results show that risk-based portfolio construction substantially improves stability. Relative to the equal-weighted benchmark, HRP reduces annualized volatility by 19.6%, daily CVaR(95%) by 19.5%, and maximum log drawdown magnitude by 23.4%. The CVaR-minimizing portfolio reduces annualized volatility by 30.5%, daily CVaR(95%) by 32.3%, and maximum log drawdown magnitude by 52.3%. These findings provide evidence that cross-resource diversification—when explicitly optimized for tail risk—can mitigate extreme downside outcomes that are relevant for environmental and resource-related uncertainty.

To assess robustness, bootstrap confidence intervals were estimated for differences in CVaR reductions across strategies. Figure 5 further illustrates the comparative risk performance of the EQ, HRP, and CVaR-min portfolios. The results confirm that the tail-risk improvements of the CVaR-min portfolio remain economically meaningful.

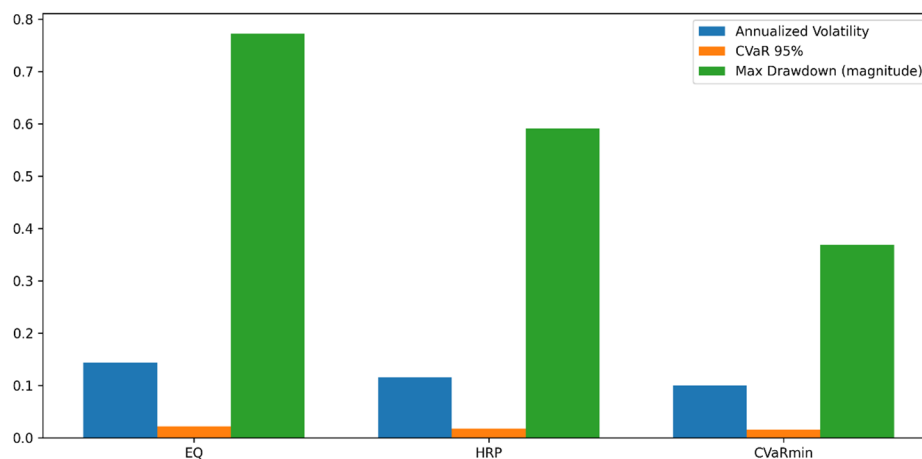


Figure 5. Portfolio risk comparison (EQ vs. HRP vs. CVaRmin).

In relative terms, the magnitude of risk reduction is economically meaningful. Compared with the equal-weight benchmark, the HRP portfolio reduces annualized volatility and CVaR (95%) by approximately 20%, while also mitigating maximum drawdown magnitude. The CVaR-minimizing portfolio provides even stronger buffering effects, with reductions exceeding 30% in both volatility and tail risk and more than 50% in maximum drawdown magnitude. These improvements highlight the effectiveness of risk-oriented cross-commodity portfolio construction in cushioning extreme downside outcomes associated with environmental uncertainty.

4.4. Regime Evidence and Dynamic Risk Dynamics

Finally, we evaluate whether cross-commodity dependence and risk characteristics change under different market regimes. Using a regime identification approach based on market volatility and average cross-commodity correlation, we distinguish between stable and stress regimes. Table 2 reports that the stress regime accounts for approximately 41.55% of observations and is characterized by substantially higher volatility and stronger cross-commodity dependence.

Table 2. Summary statistics of market risk regimes.

Regime	Proportion	Mean Mkt. Vol.	Mean Avg. Corr.
0 (Stable)	0.5845	0.1040	0.1167
1 (Stress)	0.4155	0.1686	0.2270

Market regimes are identified using an unsupervised clustering approach based on rolling market-wide volatility and average cross-commodity correlation. Portfolio buffering performance is evaluated relative to the equal-weighted benchmark using annualized volatility, CVaR (95%), and maximum drawdown measures. Regime-specific risk characteristics are summarized from Table 2, while portfolio risk reductions are derived from Table 1 and regime-based analysis.

Taken together, Tables 1 and 2 suggest that portfolio performance should be interpreted conditionally on the prevailing risk environment. HRP is more consistent with diversification under lower-correlation conditions, whereas CVaR minimization is more directly aligned with downside-risk control when volatility and dependence are elevated.

Figure 6 visualizes the rolling average correlation over time and highlights stress regime intervals. The dependence structure intensifies during stress regimes, implying that diversification benefits may become weaker when volatility and average cross-commodity correlation increase. Importantly, the portfolio comparison in Table 1 indicates that risk-based portfolios—particularly the CVaR-minimizing portfolio—retain meaningful buffering capacity even under adverse conditions, consistent with the intended role of cross-commodity portfolios as resource-price risk management under environmental and market uncertainty.



Figure 6. Rolling average cross-commodity correlation (shaded = stress regime).

While Figure 6 provides a descriptive view of correlation dynamics, the state-space results extend this analysis by capturing the latent accumulation of systemic risk beyond observable correlation spikes. This section further examines the dynamic nature of cross-commodity risk by integrating regime classification with a

continuous systemic risk measure derived from a state-space model. Figure 7 presents the smoothed latent systemic risk state, capturing the evolving intensity of common risk across commodity markets over time.

The results show that the estimated systemic risk state exhibits pronounced increases during periods identified as stress regimes, confirming a strong consistency between discrete regime classification and continuous risk dynamics. In particular, periods characterized by elevated market volatility and cross-commodity correlation are associated with significantly higher levels of the latent systemic risk state, reinforcing the interpretation that regime shifts reflect meaningful changes in the underlying risk environment rather than purely statistical artifacts.

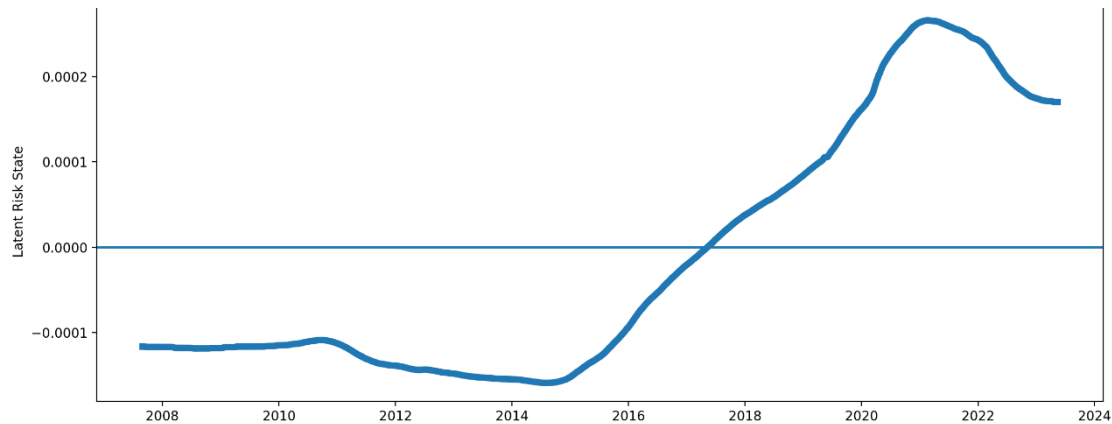


Figure 7. Smoothed systemic commodity risk estimated from the State-Space Model.

Figure 7 shows that the smoothed systemic risk state generally moves together with periods characterized by elevated market volatility and stronger cross-commodity correlation. Rather than representing abrupt shifts, the estimated latent state reflects gradual changes in the common risk environment captured from commodity market dynamics. This finding is consistent with the view that systemic risk evolves continuously over time and can be summarized through a smoothed market-based indicator. However, the estimated state should be interpreted as a descriptive representation of time-varying common market risk rather than evidence of predictive early-warning ability or causal transmission.

Taken together, these findings highlight that diversification breakdown across commodity markets is a dynamic process. The state-space results provide additional insight beyond static or threshold-based regime indicators by revealing how systemic risk evolves over time and interacts with market dependence structures. This dynamic perspective is particularly relevant in the context of environmental and resource-related uncertainty, where risk transmission mechanisms may unfold progressively rather than instantaneously.

5. Discussion

5.1. Interpretation of Cross-Commodity Risk Patterns

The focus on risk from commodity prices suggests better explanations of futures-market behavior using a resource-system approach. Increased tail risk, especially in energy-related futures, is seen as a financial response to environmental pressures, coupled supply, and systemic resource sector dependencies.

The presence of tail risk is seen in a number of agricultural commodities. The reasons include climate variability, weather disruptions, and biology's limitations. The results imply that environmental risk is not limited to one resource component and uniquely appears in related commodity systems. This means that risk assessment systems based on a single commodity may not accurately capture linked resource cross-system risks.

5.2. Systemic Dependence and the Role of Energy Markets

The dependence analysis builds on an understanding of cross-commodity risk structure. Principal components analysis shows that in a cross-commodity risk space, one dominant risk factor is captured, and is almost completely explained by energy futures. This shows how energy risks dominate in cross-commodity systemic risk. Energy markets are linked to agriculture and metals markets, with energy prices impacting production of metals and agriculture and affecting related systemic risks.

The results of the regime-partitioning method indicate that commodity risks are risk interdependent, especially under high-volatility regimes. In such markets, cross-commodity risk interdependencies are beyond simultaneous co-movement. From a resource management and sustainability perspective, this indicates the

potential for rapid propagation of environmental and market resource system shocks. It is therefore vital in any analysis of subsystems to focus on independence of cross-commodity.

5.3. Portfolio-Based Risk Management under Environmental Uncertainty

This study provides a central contribution pertaining to an understanding that when cross-commodity futures portfolios are designed to control downside risk, they can be considered effective portfolios to assist with risk management in an environmental context. Decoupled from the equal-weight benchmark, risk-oriented portfolios, especially those that minimize CVaR, generate meaningful reductions in tail risk, volatility, and the size of maximum drawdowns.

The extent of this improvement is remarkable. Compared to the benchmark portfolio, while the hierarchical risk parity strategy decreases tail risk and overall volatility by about 20%, the CVaR-minimizing strategy achieves over a 30% decrease in both tail risk and volatility, and over a 50% decrease in the size of the maximum drawdown. This is evidence supporting the notion that portfolio construction techniques emphasizing the control of tail risk can be particularly effective to absorb large resource price shocks.

While the changes are impressive, they should not be viewed as superior speculative performance. In essence, the portfolios reviewed in this study are risk-buffers; they are intended to minimize the exposure to large swings in resource prices, and not to maximize the portfolio returns.

5.4. Implications for Environmental Finance and Resource Governance

The findings are relevant for food system resilience, energy transition volatility management, climate-related financial supervision, and resource-dependent firms exposed to environmental uncertainty. The empirical findings indicate important implications for how we finance environmental issues and manage resources. First, interpretation of the connection that exists between the energy markets and systemic commodity risk, posits that energy futures may be at the center of how risk is transferred across resource markets. Keeping track of energy-related risk factors may be useful for forecasting the initial collapse of unsustainable commodity systems that are integral to the economy and the environment.

Second, the successful cross commodity, risk-based portfolio, and tail risk strategies, show how financial instruments can play an important role in reducing the uncertainty in the environment and the markets. For example, institutions, public funds, and resource-related entities that hold these instruments are likely using them to hedge against possible price shocks of a climate-related supply disruption, policy, alternative sources of energy, and/or resource shocks. These instruments offset the financial loss and may encourage riskier investments that otherwise may not be undertaken in the environmental sector.

From the perspective of governance, the estimated systemic risk state may serve as a supplementary market-based indicator that complements existing monitoring frameworks for resource-market conditions. The tracking of systemic risk may support a proactive governance system that allows for anticipatory risk frameworks, in lieu of the policy risk management systems, to be integrated into the governance systems. These risk management instruments may complement the other policy frameworks and/or risk management tools that seek to govern environmental risks.

Lastly, the regime-dependent characteristic of diversification benefits highlights the constraints of fixed risk-management techniques. Considering the numerous complex interrelated risks of environmental change and resource markets, adaptive risk-management techniques focusing on the changes in dependence structures and systemic risks are likely to be more effective.

5.5. Limitations and Future Research

Several limitations should be acknowledged. First, the study focuses on financial market manifestations of environmental risk rather than directly modeling physical variables such as temperature anomalies, drought indices, or emissions constraints. Future research could integrate financial and environmental datasets to identify more direct transmission channels.

Future studies may also explore alternative regime-identification methods, such as Markov-switching models, and extend the portfolio framework to include green financial instruments or carbon-related assets. Such extensions would further enrich the understanding of how financial markets can contribute to managing environmental and sustainability-related risks.

6. Conclusions

This research seeks to answer if cross-commodity futures portfolios can be used to hedge environmental and resource-related price risks. Using a multi-commodity dataset, the research applies portfolio construction integrated with tail risk, dependence, regimes, and risks to evaluate the extent to which environmental uncertainty is incorporated and addressed within commodity futures markets.

Strong inequality is reported in the results in the domain of risk of loss across resource types. Energy-related futures report higher volatility and tail risks, while metal and livestock contracts are reported to have more stabilizing characteristics. This inequality indicates that environmental and supply-related uncertainty across resource systems is reported to have a unique nature in that they cannot be captured through single-commodity systems. Also, the results report that the major common determinant is driven by meta-systems of energy, and as such, results appear to show that the meta-systems of energy are the primary driving factor in the spread of systemic risk across all traded commodities.

The portfolio results show that cross-commodity portfolio diversification, when hedge-oriented, is reported to have a meaningful and substantial impact on controlling the extent of extreme loss. In relation to the equal weight baseline, both the hierarchical risk parity and the portfolio that minimizes CVaR are reported to have a positive and meaningful impact on the reduction in tail risk. These effects are sustained during extreme risk regimes that are reported to have high volatility and an increased level of inter-commodity correlations.

Looking at the study as a whole, the results add to the existing knowledge on environmental finance and ecological economics by demonstrating the role financial market instruments play alongside other environmental risk management options. When looking at cross-commodity futures, the argument is made that they can be understood as stabilizing mechanisms, instead of looking at them purely as speculative instruments. When resource-system uncertainties include environmental change, resource depletion, and systemic interdependencies, cross-commodity futures portfolios may help policymakers, institutional investors, and resource-dependent businesses address uncertainties by expediting the stabilization process of the financial market.

Despite this study being about financial market prices, the boundaries of this study can help lay the framework for conducting other studies that target the environmental aspects. Incorporating environmental aspects can be used to improve the understanding of how risks related to environmental changes can be absorbed by economic and financial systems. In fact, the use of cross-commodity futures provides an opportunity to add financial risk management to the ongoing environmental resource governance and related management challenges.

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Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data used in this study were obtained from the publicly available “Commodities Futures Collection” dataset on Kaggle (<https://www.kaggle.com/datasets/guillemservera/commodities-futures-collection>). The dataset contains historical futures price series across multiple commodity categories, including energy, agricultural products, metals, and livestock. All data are publicly accessible. The processed datasets and replication code supporting the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The author declares no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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