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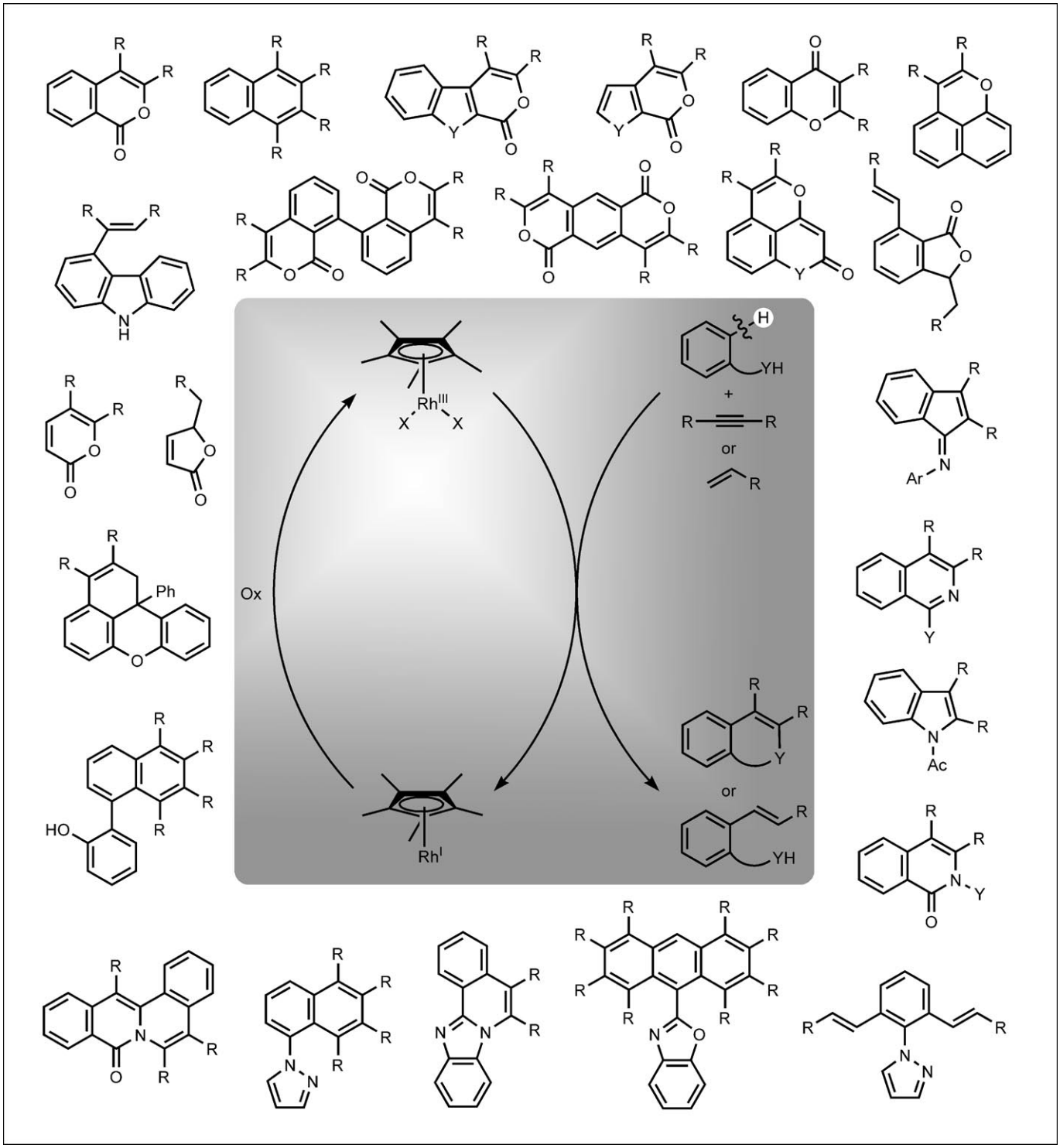
Oxidative Coupling of Aromatic Substrates with Alkynes and Alkenes under Rhodium Catalysis

Tetsuya Satoh* and Masahiro Miura*[a]



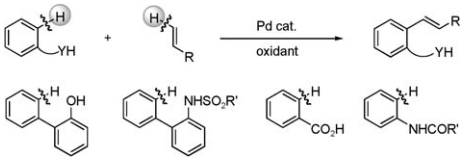
Abstract: Aromatic substrates with oxygen- and nitrogen-containing substituents undergo oxidative coupling with alkynes and alkenes under rhodium catalysis through regioselective C–H bond cleavage. Coordination of the substituents to the rhodium center is the key to activate the C–H bonds effectively. Various fused-ring systems can be constructed through these reactions.

Keywords: C–H activation · fused-ring systems · homogeneous catalysis · oxidative coupling · rhodium

Introduction

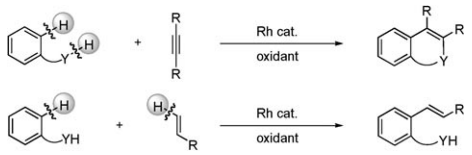
Transition-metal-catalyzed organic reactions through C–H bond cleavage have attracted much attention from the atom- and step-economical points of view, and a variety of catalytic processes that use different modes for activating the ubiquitously available bond have been developed.[1] Among the most promising activation strategies is to utilize the proximate effect by coordination of a functional group in a given substrate to the metal center of a catalyst that leads to regioselective C–H bond activation and functionalization. As the pioneering work in this area, Murai and coworkers reported the ruthenium-catalyzed coupling of aromatic ketones with alkenes involving regioselective C–H activation at the *ortho* position.[2] Then, the coupling of various aromatic substrates with heteroatom-containing functional groups with alkenes and alkynes have been developed.

The oxidative coupling reactions of these substrates, on the other hand, are highly useful as synthetic methods for π-conjugated molecules. In 1981, Horino and Inoue disclosed the stoichiometric *ortho*-vinylation of acetanilides with alkenes in the presence of $Pd(OAc)_2$.[3] After a 15 year hiatus, early examples of the catalytic version involving a Pd^{II}/Pd^0 cycle were reported (Scheme 1).[4] Thus, we succeeded in conducting the palladium-catalyzed oxidative coupling of 2-phenylphenols,[4a] *N*-sulfonyl-2-phenylanilines,[4b] and benzoic acids[4b] with alkenes by using $Cu(OAc)_2$ and air as the cocatalyst and terminal oxidant, respectively. The catalytic *ortho*-vinylation of acetoanilides was also reported by de Vries and co-workers.[4c] In this reaction, 1,4-benzoquinone and *p*-toluenesulfonic acid were employed as the oxidant and promoter, respectively. Later, the reactions of benzylamines[5] and pyridine *N*-oxides[6] were developed. In spite of such evolution, the scope of substrates for the oxidative coupling is still limited. Furthermore, high palladium loadings and/or acid and metal salt additives are usually required for realizing practical reaction efficiency. Without such elaboration, the homogeneous palladium-based catalysts tend to decompose into inactive bulk metal.[7]



Scheme 1. Early examples of Pd-catalyzed oxidative coupling by regioselective C–H bond cleavage.

On the other hand, the Rh^{III}/Rh^{I} process, as well as Pd^{II}/Pd^0, is also known to be applicable to organic oxidation reactions.[1a,8] Around 40 years ago, the rhodium-catalyzed oxidation of olefins was extensively investigated[9] in addition to a well-known palladium-catalyzed version, that is, the Wacker process. Since then, the rhodium catalyst systems for oxidation have been less explored than those with palladium. In 2000, Matsumoto and Yoshida reported an example for the oxidative coupling of benzene with ethylene under rhodium catalysis.[10] The reactions of other substrates were not examined. For the last four years, however, the rhodium-catalyzed oxidative couplings of various aromatic substrates with alkynes and alkenes have been extensively investigated (Scheme 2). Essentially, the turnover numbers of the rhodium catalysts in such reactions are much higher than those of palladium. Herein, these selective coupling reactions are summarized by the identity of substrate categories.



Scheme 2. Rh-catalyzed oxidative coupling of aromatic substrates with alkynes and alkenes by regioselective C–H bond cleavage.

Coupling of Carboxylic Acids

A carboxyl function is known to act as a unique, removable directing group. A number of palladium-catalyzed arylation reactions at the *ortho* and *ipso* positions of the key function have been reported.[1b,c,11] The oxidative vinylation around the function principally using palladium catalysts has also been developed.[4b,12] Although it has been shown by Maitlis

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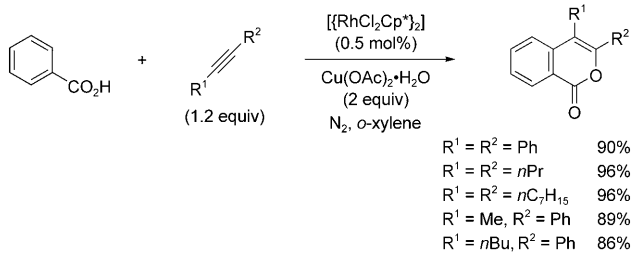
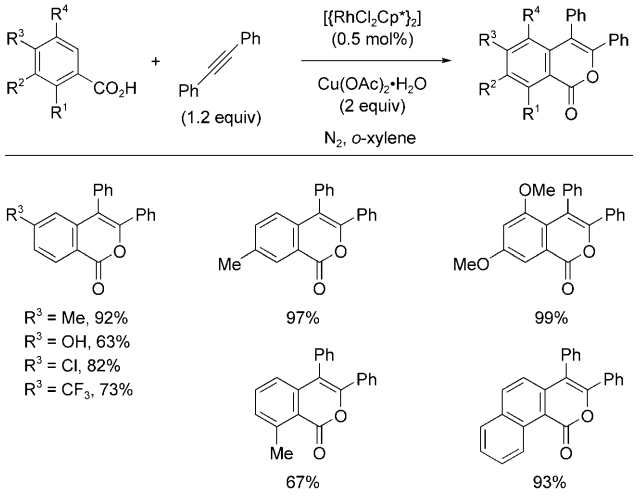
and co-workers that the carboxyl group can act as a good anchor for the stoichiometric cyclometalation on rhodium complexes,[13] catalytic reactions involving such a step have been scarcely explored.

In 2007, we reported the rhodium-catalyzed oxidative coupling of benzoic acids with internal alkynes (Scheme 3).[14] Thus, treatment of benzoic acid with diphenylacetylene (1.2 equiv) using [{$RhCl_2Cp^*$}$_2$] (0.5 mol%; Cp^* = η^5-pentamethylcyclopentadienyl) and $Cu(OAc)_2 \cdot H_2O$ (2 equiv) in *o*-xylene under N_2 affords a 1:1 coupling product, 3,4-diphenylisocoumarin, in 90% yield, along with a small amount of 1,2,3,4-tetraphenylnaphthalene (3%). None or trace amounts of the coupling products can be obtained when using $RhCl_3 \cdot H_2O$, [Rh(acac)$_3$], [{RhCl(cod)}$_2$], or [{$RhCl(C_2H_4)_2$}$_2$] in place of [{$RhCl_2Cp^*$}$_2$] (acac = acetylacetonate, cod = cyclooctadiene). Under the conditions using [{$RhCl_2Cp^*$}$_2$] as the catalyst, dialkylacetylenes, such as 4-octyne and 8-hexadecyne, also undergo the coupling with benzoic acid smoothly to produce the corresponding 3,4-dialkylisocoumarins in good yields. The reactions of unsymmetrical alkylphenylacetylenes give 4-alkyl-3-phenylisocoumarins predominantly.



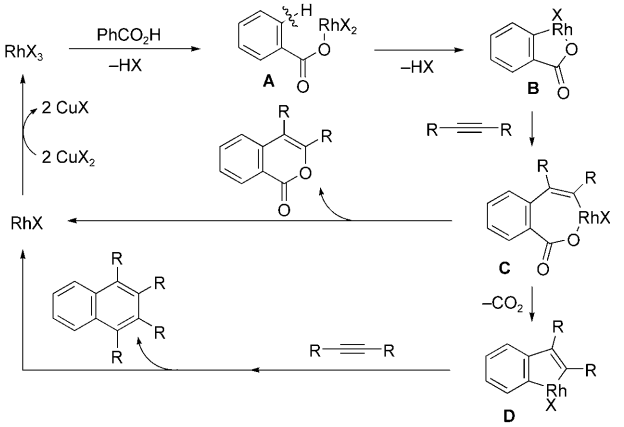
Scheme 3. The 1:1 coupling of benzoic acid with alkynes.

From the reactions of *p*-, *m*-, and *o*-substituted benzoic acids with diphenylacetylene, the corresponding isocoumarins can be obtained (Scheme 4). The reaction using 1-naphthoic acid in place of benzoic acids needs the solvent to be heated at reflux for efficient coupling.



Scheme 4. The 1:1 coupling of benzoic acids with diphenylacetylene.

A plausible mechanism for the oxidative coupling is illustrated in Scheme 5, in which neutral ligands are omitted for clarity. Coordination of the carboxylate oxygen to the [$Rh^{III}Cp^*X_2$] species gives an Rh^{III} benzoate **A**. Subsequent cyclorhodation to form a rhodacycle intermediate **B**,[13] alkyne insertion, and reductive elimination occur to produce an isocoumarin. The resulting Cp^*Rh^I species may be oxi-



Scheme 5. A plausible mechanism for the coupling of benzoic acid with alkynes.

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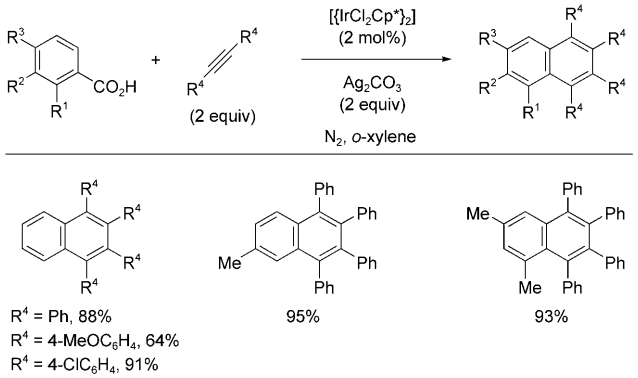
Masahiro Miura is a professor of the Graduate School of Engineering, Osaka University. He studied chemistry at Osaka University and received his Ph.D. degree in 1983 under the guidance of Prof. S. Kusabayashi and Prof. M. Nojima. After working in the chemical industry for one and a half years, he started his academic career as research associate at Osaka University. He was promoted to associate professor in 1994 and to full professor in 2005. He also worked as a Humboldt fellow with Prof. K. Griesbaum at the Karlsruhe University (Germany) in 1990–1991. His current research interests include transition metal catalysis and the synthesis of functional molecules, especially new π-conjugated aromatic substances.

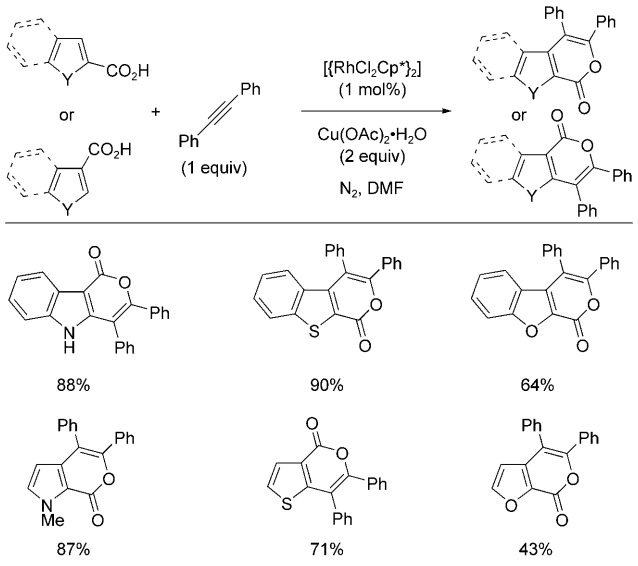
dized in the presence of a Cu^{II} salt to regenerate $[Rh^{III}Cp^*X_2]$. The minor product, 1,2,3,4-tetrasubstituted naphthalenes, may be obtained by decarboxylation of **C** to form **D**, the second alkyne insertion, and reductive elimination.

From the same substrates, benzoic acids and alkynes, 1,2,3,4-tetrasubstituted naphthalenes can be exclusively produced by using $[\{IrCl_2Cp^*\}_2]$ and Ag_2CO_3 as the catalyst and oxidant, respectively (Scheme 6).

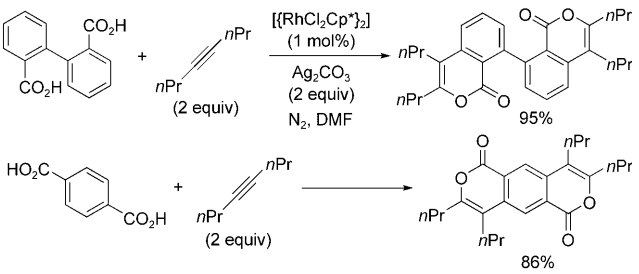


Scheme 6. The 1:2 coupling of benzoic acids with alkynes.

Besides benzoic and naphthoic acids, heteroarene carboxylic acids and aromatic diacids also undergo oxidative coupling in DMF with diphenylacetylene and 4-octyne, respectively.[15] As shown in Schemes 7 and 8, complicated bi- and tricyclic systems can be constructed effectively through the process. In the reactions of diacids, the use of Ag_2CO_3 as oxidant is essential. With $Cu(OAc)_2{\cdot}H_2O$, no desired products are obtained.

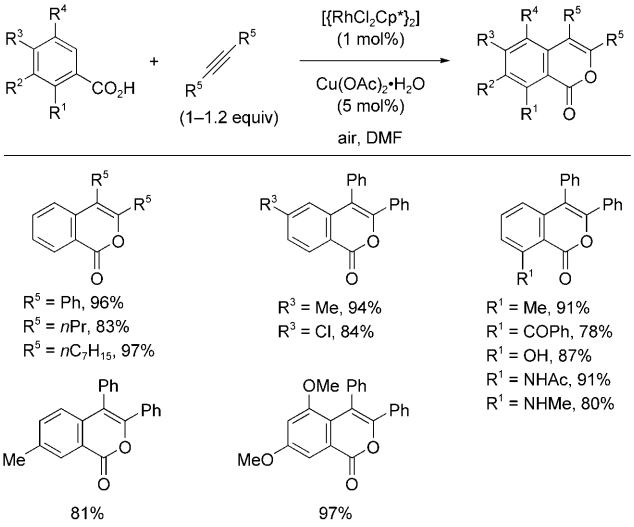


Scheme 7. The 1:1 coupling of heteroarene carboxylic acids with diphenylacetylene.



Scheme 8. The 1:2 coupling of aromatic diacids with 4-octyne.

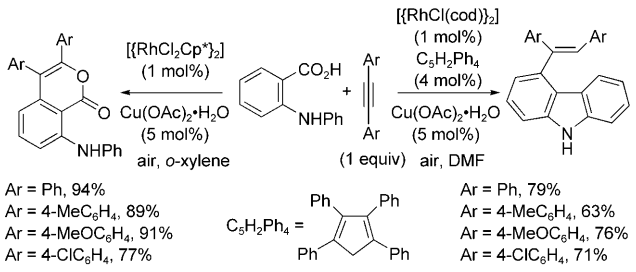
Interestingly, the reaction of benzoic acids with alkynes takes place efficiently even with a reduced amount (5 mol%) of $Cu(OAc)_2{\cdot}H_2O$ under air.[14] Thus, the aerobic oxidative coupling using a catalyst system of $[\{RhCl_2Cp^*\}_2]$/$Cu(OAc)_2{\cdot}H_2O$ proceeds in DMF to afford the corresponding isocoumarins in good to excellent yields (Scheme 9). In particular, anthranilic and salicylic acid derivatives smoothly undergo the reaction to produce 8-amino- and 8-hydroxyisocoumarins,[15] which are known to exhibit a broad range of interesting biological and photochemical properties.[16]



Scheme 9. The 1:1 aerobic oxidative coupling of benzoic acids with diphenylacetylene.

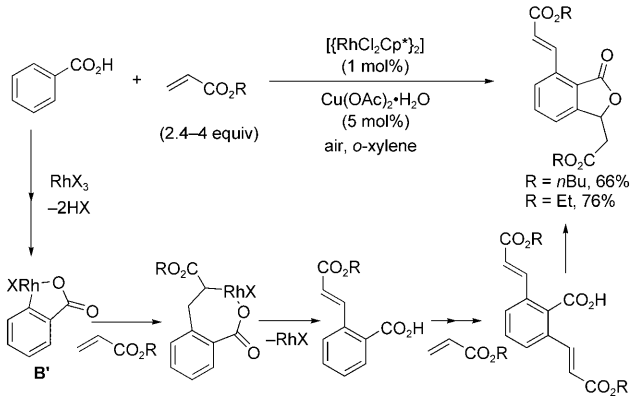
N-Phenylanthranilic acid also reacts with diarylacetylenes under aerobic conditions in *o*-xylene to form the corresponding 8-(*N*-phenylamino)isocoumarins in good yields (Scheme 10). However, the use of a different rhodium catalyst system, $[\{RhCl(cod)\}_2]/C_5H_2Ph_4$, in place of $[\{RhCl_2Cp^*\}_2]$ dramatically changes the reaction pathway ($C_5H_2Ph_4$ = 1,2,3,4-tetraphenyl-1,3-cyclopentadiene). Thus, the reaction with this catalyst in DMF proceeds through double C–H bond cleavage and decarboxylation to afford 4-(1,2-diarylethenyl)-9*H*-carbazoles.

Under the aerobic conditions, benzoic acid also reacts not only with alkynes, but also with alkenes such as acrylates



Scheme 10. The 1:1 coupling of *N*-phenylanthranilic acid with diarylacetylenes.

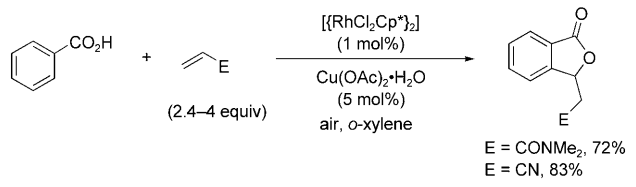
smoothly (Scheme 11).[14] In contrast to the Pd-catalyzed 1:1 coupling of these substrates,[4b] their 1:2 coupling involving disubstitution at both the *ortho* positions of benzoic acid



Scheme 11. The 1:2 coupling of benzoic acid with acrylates.

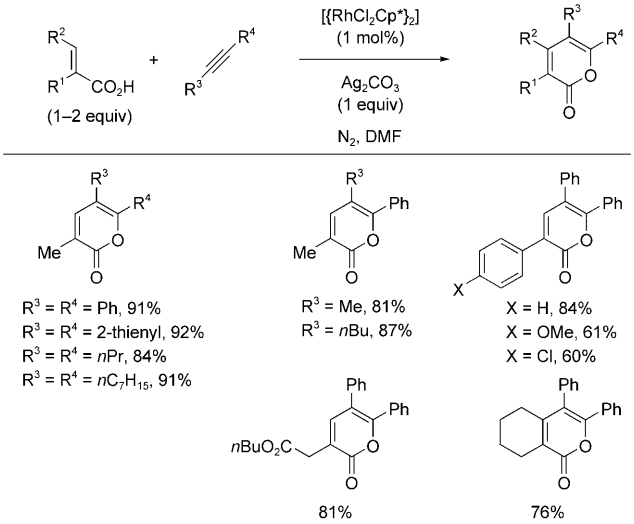
takes place to afford 7-vinylphthalides selectively. In these cases, a rhodacycle intermediate **B′**, generated in a similar manner to that in the reaction with alkynes (**B** in Scheme 5), may undergo alkene insertion and successive β-hydride elimination to form an *ortho*-monovinylated benzoic acid. The second vinylation takes place through similar steps to lead to a 2,6-divinylated benzoic acid, which may undergo nucleophilic cyclization to yield the final product.

In contrast to the acrylates, *N*,*N*-dimethylacrylamide and acrylonitrile react with benzoic acid in a 1:1 manner under similar conditions (Scheme 12). In the cases with these alkenes, the cyclization exclusively occurs after the first vinylation (see Scheme 11), as occurs in the Pd-catalyzed reaction.[4b]

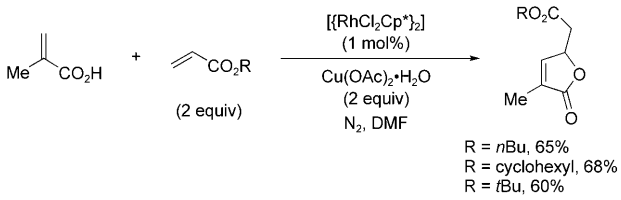


Scheme 12. The 1:1 coupling of benzoic acid with alkenes.

Under rhodium catalysis, acrylic acids also oxidatively couple with alkynes and alkenes through vinylic C–H bond cleavage (Schemes 13 and 14).[17] These reactions with stoichiometric amounts of Ag_2CO_3 or $Cu(OAc)_2{\cdot}H_2O$ as the oxidant give α-pyrone and butenolide derivatives efficiently.



Scheme 13. The 1:1 coupling of acrylic acids with alkynes.



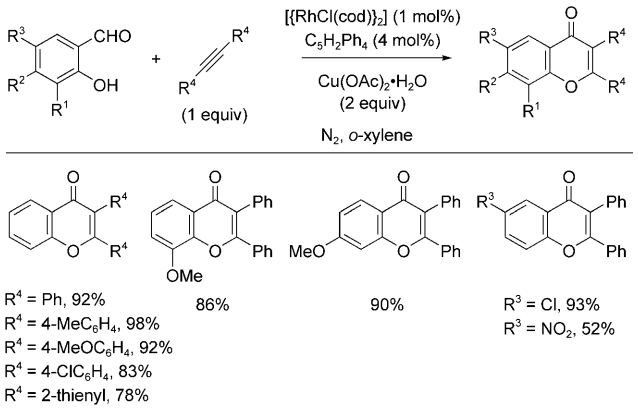
Scheme 14. The 1:1 coupling of methacrylic acid with alkenes.

Coupling of Phenols and Alcohols

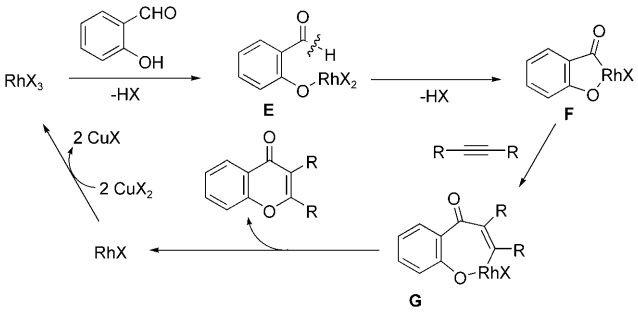
It is known that salicylaldehydes,[18] 1-naphthols,[19] and 2-phenylphenols[19] undergo direct arylation through regioselective C–H bond cleavage around their hydroxyl function upon treatment with aryl halides in the presence of palladium catalysts. As expected, under conditions using rhodium catalysts and appropriate oxidants, these substrates oxidatively couple with alkynes through the C–H bond cleavage at the same positions to form fused aromatic products.

The reaction of salicylaldehydes with diarylacetylenes in the presence of $[\{RhCl(cod)\}_2]/C_5H_2Ph_4$ and $Cu(OAc)_2{\cdot}H_2O$ as the catalyst and oxidant, respectively, proceeds by aldehyde C–H bond cleavage to afford 2,3-diarylchromones in good yields (Scheme 15).[20]

A plausible mechanism for the reaction of salicylaldehyde with alkynes is illustrated in Scheme 16. Coordination of the phenolic oxygen atom to a $Rh^{III}X_3$ species gives a Rh^{III} phenolate **E**. Then, directed C–H rhodation to form a rhodacycle intermediate **F**,[21,22] alkyne insertion, and reductive elimination take place to form a chromone. The resulting $Rh^{I}X$



Scheme 15. The 1:1 coupling of salicylaldehydes with alkynes.



Scheme 16. A plausible mechanism for the coupling of salicylaldehyde with alkynes.

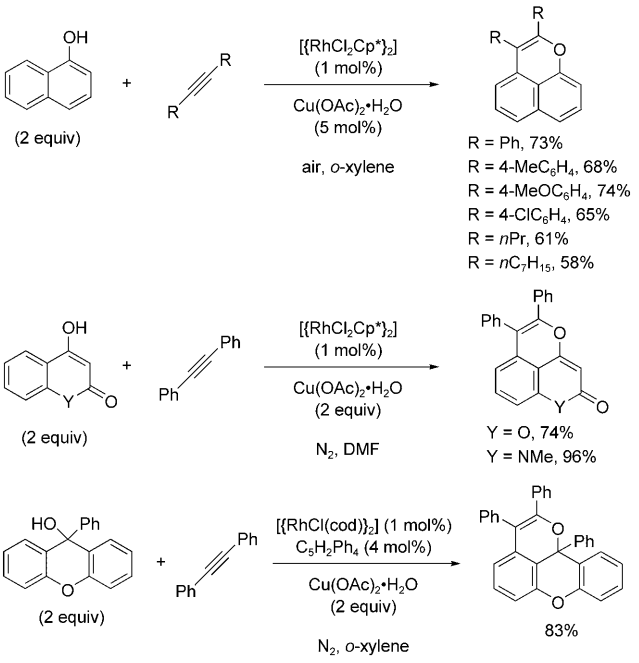
species may be oxidized in the presence of a Cu^{II} salt to regenerate $Rh^{III}X_3$. While the exact role of the added $C_5H_2Ph_4$ ligand is not clear, it may support the unstable Rh^{I} species during the reoxidation step to prolong the lifetime of the catalyst.

The reactions of 1-naphthols and analogues including 4-hydroxycoumarin and -quinolinone and 9-phenylxanthen-9-ol involve *peri* C–H bond cleavage to produce fused pyran derivatives (Scheme 17).[23]

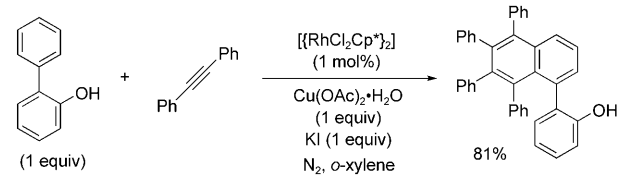
In contrast to such 1:1 couplings described above, 2-phenylphenols reacted with alkynes in a ratio of 1:2 (Scheme 18). Thus, treatment of equimolar amounts of 2-phenylphenol, diphenylacetylene, $Cu(OAc)_2•H_2O$, and KI in the presence of $[\{RhCl_2Cp^*\}_2]$ (1 mol%) selectively gave 5-(2-hydroxyphenyl)-1,2,3,4-tetraphenylnaphthalene in 81% yield.

The rhodium-catalyzed oxidative coupling of triarylmethanols with alkynes proceeds through a unique pathway, which involves the successive cleavages of C–H and C–C bonds with elimination of diaryl ketones.[24] The alcohols react with diarylacetylenes efficiently in the presence of $[\{RhCl(cod)\}_2]/C_5H_2Ph_4$ and $Cu(OAc)_2•H_2O$ as the catalyst and oxidant, respectively, to afford 1,2,3,4-tetraarylnaphthalenes (Scheme 19).

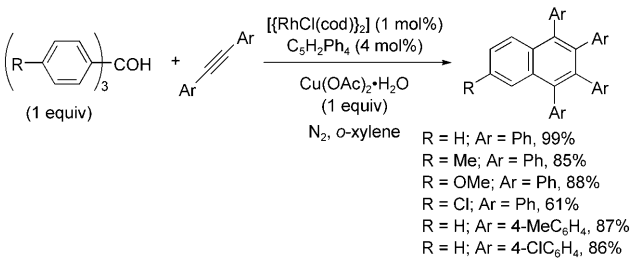
Interestingly, the reaction with dialkylacethylenes can be conducted smoothly by using $[\{RhCl_2Cp^*\}_2]/C_5H_3Ph_3$



Scheme 17. The 1:1 coupling of 1-naphthols and analogues with alkynes.



Scheme 18. The 1:2 coupling of 2-phenylphenol with diphenylacetylene.

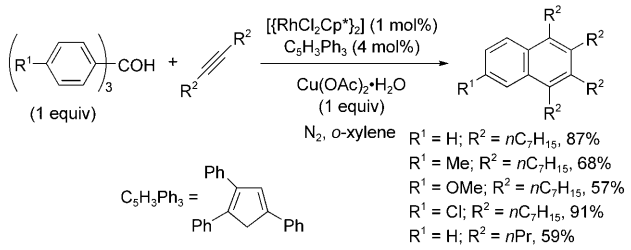


Scheme 19. The 1:2 coupling of triarylmethanols with diarylacetylenes.

$(C_5H_3Ph_3 = 1,2,4\text{-triphenyl-1,3-cyclopentadiene})$ in place of $[\{RhCl(cod)\}_2]/C_5H_2Ph_4$ (Scheme 20).

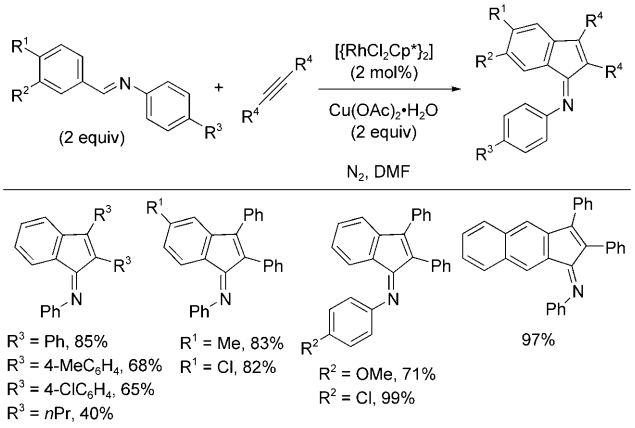
Coupling of Imines

Imino groups are also widely utilized as the directing group for regioselective C–H functionalization under rhodium catalysis.[1h,o,25] We succeeded in conducting the oxidative coupling of *N*-benzylideneanilines with alkynes by using $[\{RhCl_2Cp^*\}_2]$ (2 mol%) and $Cu(OAc)_2•H_2O$ (2 equiv) as



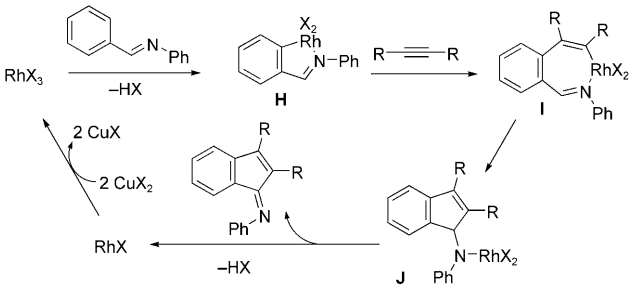
Scheme 20. The 1:2 coupling of triarylmethanols with dialkylacetylenes.

the catalyst and oxidant, respectively, in DMF under N_2 to produce indenone imines (Scheme 21).[26]



Scheme 21. The 1:1 coupling of *N*-benzylideneanilines with alkynes.

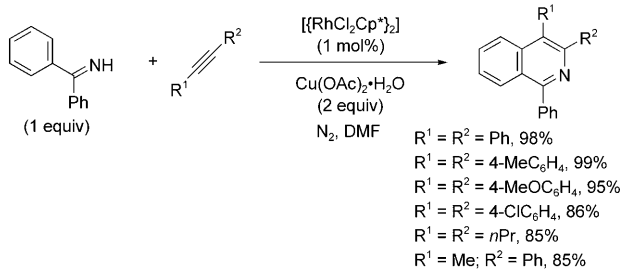
A plausible mechanism for the reaction of *N*-benzylideneaniline with alkynes is illustrated in Scheme 22. Coordination of the nitrogen atom of the imine to a $Rh^{III}X_3$ species



Scheme 22. A plausible mechanism for the coupling of *N*-benzylideneaniline with alkynes.

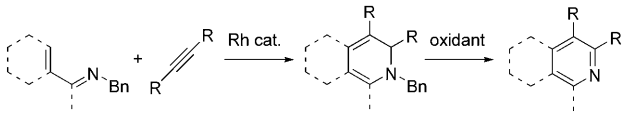
leads to the regioselective C–H bond cleavage to afford **H**. Then, alkyne insertion to form **I**, intramolecular insertion of the imino moiety to form **J**, and β-hydrogen elimination may successively occur to give an indenone imine. The $Rh^{I}X$ species, formed by release of HX, may be reoxidized by $Cu^{II}X_2$.

Under similar conditions, benzophenone imine efficiently undergoes the oxidative coupling with alkynes accompanied by C–H and N–H bond cleavages to form isoquinolines in good yields (Scheme 23).



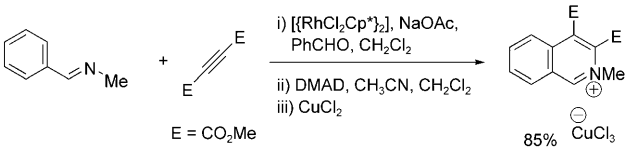
Scheme 23. The 1:1 coupling of benzophenone imine with alkynes.

As other approaches toward isoquinoline and pyridine derivatives, two-step syntheses of them though the Rh^{I}-catalyzed *ortho*- and β-vinylation of *N*-benzylimines with alkynes and subsequent oxidative aromatization were reported by the groups of Jun[27] and Bargman and Ellman,[28] respectively (Scheme 24).



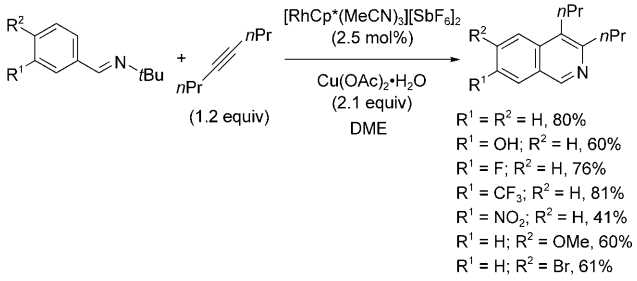
Scheme 24. The 1:1 coupling of N-benzylimines with alkynes.

Jones and co-workers reported the stoichiometric construction of an isoquinoline salt on a Cp^*Rh^{III} complex by oxidative coupling of *N*-benzylidenemethylamine with dimethyl acetylenedicarboxylate (DMAD) with the aid of $CuCl_2$ (Scheme 25).[29,30]



Scheme 25. The 1:1 coupling of N-benzylidenemethylamine with DMAD.

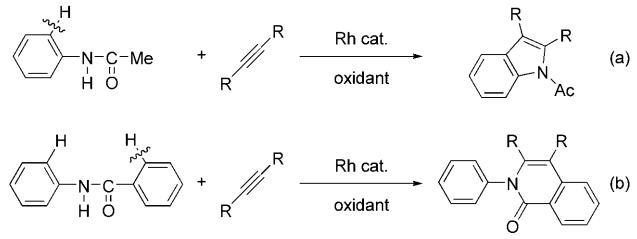
A single-step catalytic synthesis of isoquinolines from *N*-alkylimines was achieved by Fagnou and Guimond.[31] Thus, treatment of *N*-benzylidene-*tert*-butylamines with alkynes (1.2 equiv) in the presence of $[RhCp^*(MeCN)_3][SbF_6]_2$ (2.5 mol%) and $Cu(OAc)_2{\cdot}H_2O$ (2.1 equiv) in dichloroethane gives the corresponding 3,4-disubstituted isoquinolines (Scheme 26).



Scheme 26. The 1:1 coupling of N-benzylidene-*tert*-butylamines with alkynes.

Coupling of Amides

In 2008, Fagnou and co-workers reported that acetanilides oxidatively couple with alkynes by using a Cp^*Rh^{III} catalyst and $Cu(OAc)_2 \cdot H_2O$ as the oxidant by *ortho*-C–H bond cleavage to afford *N*-acetylindoles (Scheme 27, route a).[32]



Scheme 27. The 1:1 coupling of N-acylanilines with alkynes.

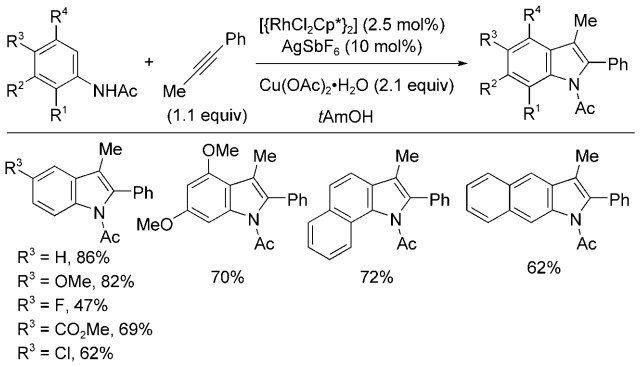
Meanwhile, we found that benzanilides, which possess two kinds of cleavable *ortho*-C–H bonds on anilino and benzoyl moieties, undergo the oxidative coupling with alkynes involving the selective cleavage of the latter to produce isoquinolinone derivatives (Scheme 27, route b).[33]

The reaction of substituted acetanilides with 1-phenyl-1-propyne (1.1 equiv) proceeds smoothly under the conditions with $[\{RhCl_2Cp^*\}_2]$ (2.5 mol%), $AgSbF_6$ (10 mol%), and $Cu(OAc)_2 \cdot H_2O$ (2.1 equiv) in *tert*-amyl alcohol, in which a similar active species to that in the reaction of *N*-benzylidene-*tert*-butylamines described in Scheme 26 may be generated (Scheme 28).[32]

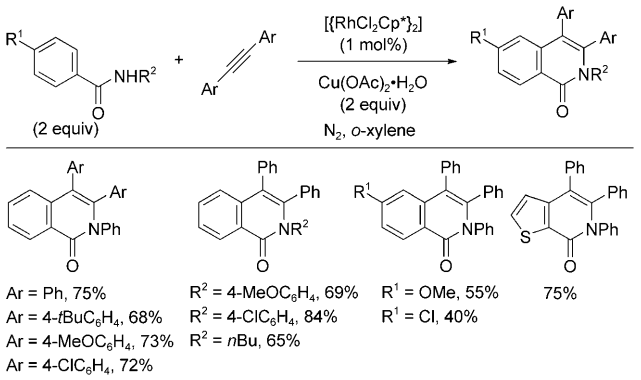
The reaction of *N*-monosubstituted benzamides, including benzanilides, with diarylacetylenes can be conducted with a more simple catalyst system without the silver salt.[33] Thus, in the presence of $[\{RhCl_2Cp^*\}_2]$ (1 mol%) and $Cu(OAc)_2 \cdot H_2O$ (2 equiv) in *o*-xylene, isoquinolinones can be obtained selectively (Scheme 29).

Under similar conditions, N-unsubstituted benzamides undergo 1:2 coupling accompanied by two C–H and two N–H bond cleavages to construct a tetracyclic dibenzoquinolizinone framework (Scheme 30).

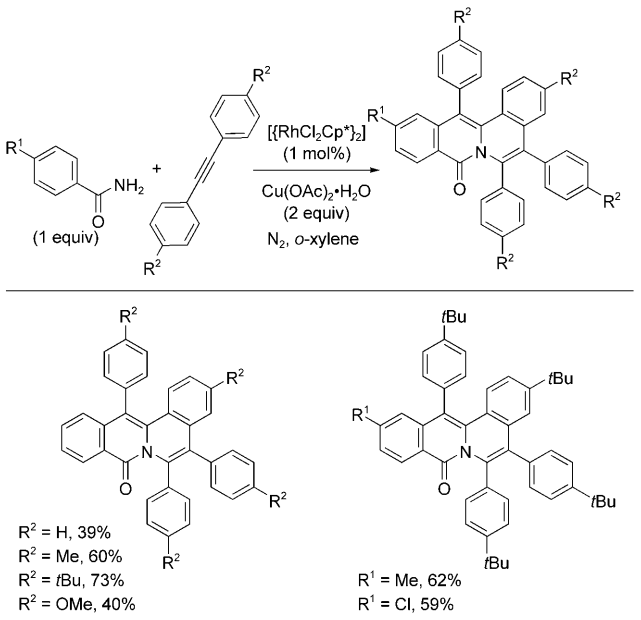
A plausible mechanism for the 1:2 coupling of benzamide with diphenylacetylene by directed metalation involving intermediates **K**–**O** is illustrated in Scheme 31. In the cyclorhodation steps from **K** and **N**, coordination of the nitrogen atom to a Rh^{III} species appears to be the key for the regioselective C–H bond cleavage.



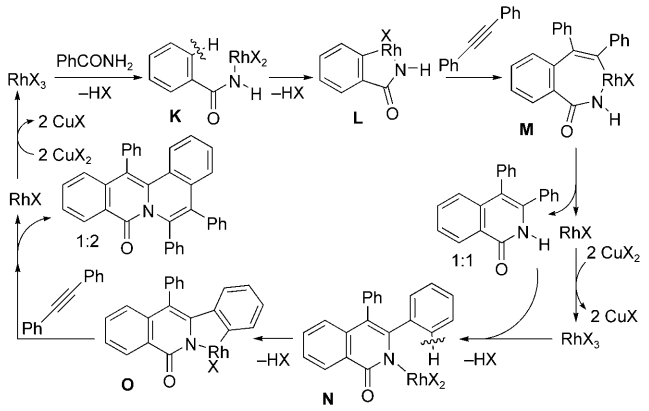
Scheme 28. The 1:1 coupling of acetanilides with 1-phenyl-1-propyne.



Scheme 29. The 1:1 coupling of N-monosubstituted benzamides with diarylacetylenes.



Scheme 30. The 1:2 coupling of N-unsubstituted benzamides with diarylacetylenes.

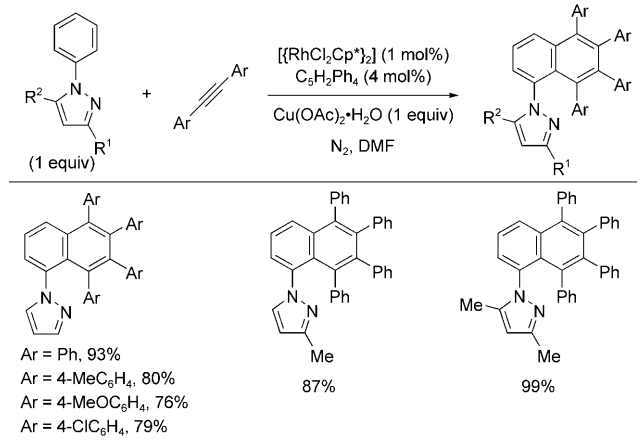


Scheme 31. A plausible mechanism for the coupling of benzamide with diphenylacetylenes.

Coupling of Phenylazoles and Phenylpyridines

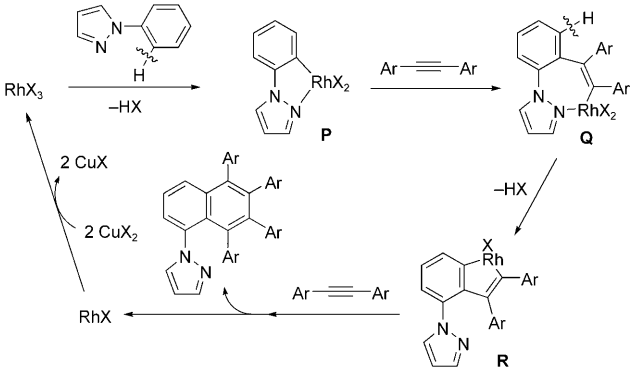
Coordination of the nitrogen atom of phenylazoles and phenylpyridines toward metal center has been widely utilized for regioselective C–H functionalization on their phenyl group.[1] These substrates also undergo oxidative coupling with alkynes and alkenes under rhodium catalysis as described below.

1-Phenylpyrazoles react with diarylacetylenes in the presence of $[\{RhCl_2Cp^*\}_2]$ (1 mol%), $C_5H_2Ph_4$ (4 mol%), and $Cu(OAc)_2{\cdot}H_2O$ (1 equiv) in DMF under N_2 to afford the corresponding 1-(1,2,3,4-tetraarylnaphthalen-5-yl)pyrazoles as 1:2 coupling products in good yields (Scheme 32).[34]



Scheme 32. The 1:2 coupling of 1-phenylpyrazoles with diarylacetylenes.

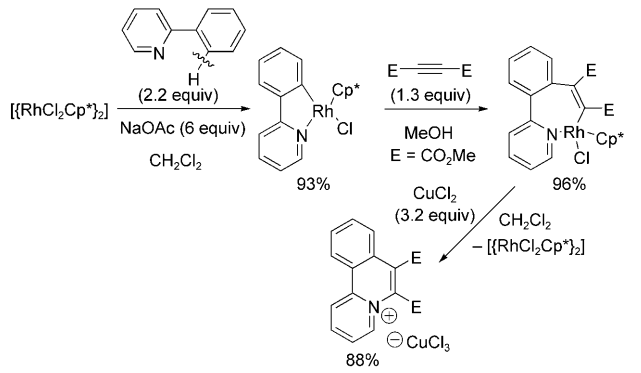
The 1:2 coupling of 1-phenylpyrazole with alkynes seems to proceed through the steps shown in Scheme 33. Coordination of the 2-N atom of 1-phenylpyrazole to a $Rh^{III}X_3$ species appears to be the key for the regioselective C–H bond cleavage to afford **P**. Then, alkyne insertion into the C–Rh bond of **P** to form **Q** and the second cyclorhodation on its phenyl ring may occur to afford **R**. Subsequently, the second



Scheme 33. A plausible mechanism for the coupling of 1-phenylpyrazole with alkynes.

alkyne insertion and reductive elimination take place to produce a 1-naphthylpyrazole as a 1:2 coupling product.

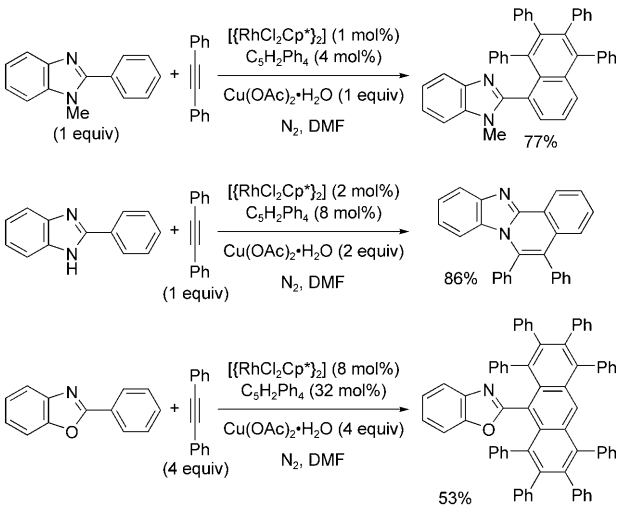
The stoichiometric formation of a seven-membered rhodacycle complex by similar cyclorhodation of 2-phenylpyridine[29,35] and alkyne insertion into the Cp^*Rh^{III} species was reported by Jones and co-workers (Scheme 34).[29] Treatment of this complex with $CuCl_2$ induces oxidative coupling of the C–N bond to liberate a benzo[*a*]quinolizinium salt, rather than the second cyclorhodation and alkyne insertion toward the 1:2 coupling.



Scheme 34. The 1:1 coupling of 2-phenylpyridine with DMAD.

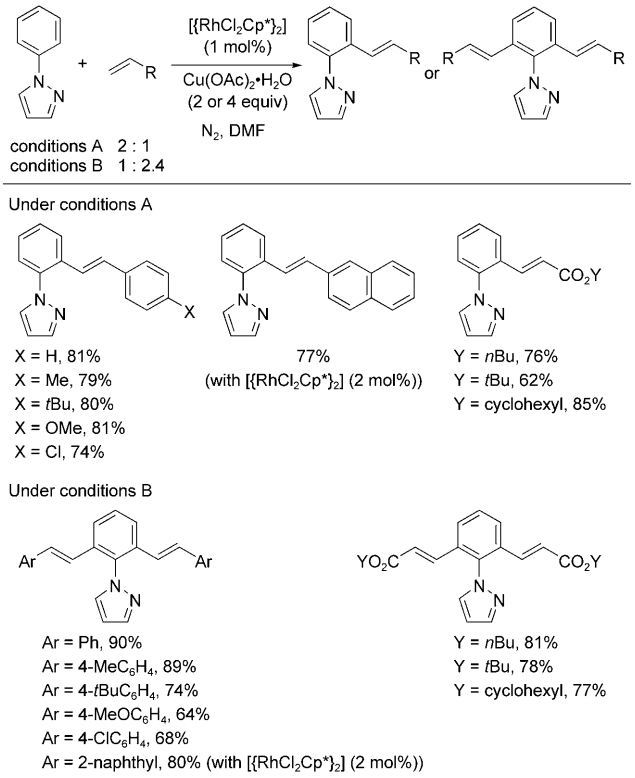
Similarly, the reaction of 1-methyl-2-phenyl-1*H*-benzimidazole with diphenylacetylene gives a 2-naphthylbenzimidazole as the 1:2 coupling product (Scheme 35). In contrast, 2-phenyl-1*H*-benzimidazole undergoes the reaction with the alkyne in a 1:1 manner through C–H and N–H bond cleavages to selectively produce an imidazoisoquinoline. Interestingly, treatment of 2-phenylbenzoxazole with diphenylacetylene (4 equiv) affords a 1:4 coupling product, 2-(1,2,3,4,5,6,7,8-octaphenylanthracen-9-yl)benzoxazole through the cleavage of four C–H bonds.

The oxidative coupling of 1-phenylpyrazoles with alkenes also proceeds efficiently under conditions using the $[\{RhCl_2Cp^*\}_2]/Cu(OAc)_2{\cdot}H_2O$ catalyst system.[36] Depending on the ratio of substrates used, their 1:1 and 2:1 couplings



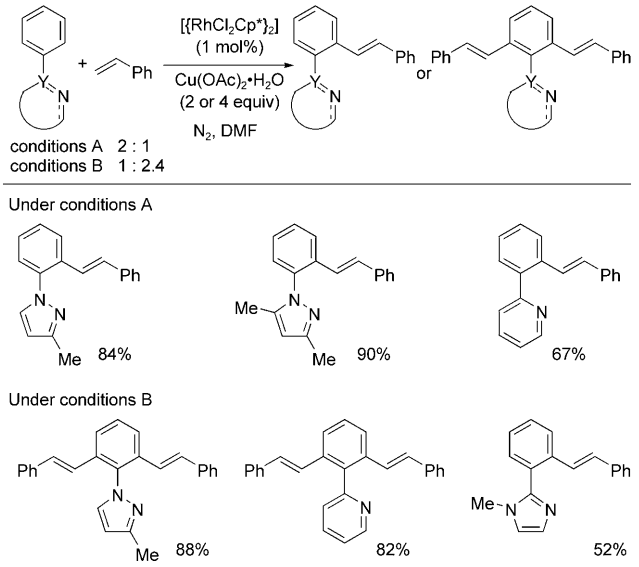
Scheme 35. Coupling of phenylazoles with diphenylacetylenes.

selectively take place. Thus, the reaction using an excess amount of 1-phenylpyrazole (2 equiv) with various styrenes or acrylates in the presence of $[\{RhCl_2Cp^*\}_2]$ (1 mol%) and $Cu(OAc)_2 \cdot H_2O$ (2 equiv) under N_2 in DMF (conditions A) affords 1-(2-vinylphenyl)pyrazoles predominantly (Scheme 36). Meanwhile, the use of these substrates in a ratio of 1:2.4 (conditions B) results in the exclusive formation of 1-(2,6-divinylphenyl)pyrazoles. In the reactions with *tert*-butyl and cyclohexyl acrylates the corresponding vinylated products are given as mixtures of geometrical isomers. However, treatment of the *E*–*Z* mixtures with $[PdCl_2(PhCN)_2]$ can induce isomerization around their C=C double bonds to form thermodynamically stable *E* and *E*,*E* isomers.[37]



Scheme 36. Coupling of 1-phenylpyrazole with alkenes.

The mono- and divinylations of other phenylazoles and a phenylpyridine with styrene can also be conducted under conditions A and B (Scheme 37). 3-Methyl-1-phenylpyrazole and 2-phenylpyridine undergo the reaction under conditions A and B to selectively afford the corresponding mono- and divinylated products, respectively. In contrast, the divinylations of sterically more hindered 3,5-dimethyl-1-phenylpyrazole and 1-methyl-2-phenylimidazole are sluggish, and monovinylated products are produced predominantly under both conditions A and B.



Scheme 37. Coupling of phenylazoles and phenylpyridine with styrene.

Summary and Outlook

The rhodium-catalyzed oxidative coupling reactions of aromatic substrates with oxygen- and nitrogen-containing substituents with alkynes and alkenes through regioselective C–H bond cleavage have been developed significantly in recent years.[38] These new reactions provide useful methods for preparing a variety of π-conjugated molecules from simple, readily available substrates. Further effort will be made to extend the scope of starting materials for this catalysis.

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